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FINAL REPORT

AN INVESTIGATION OF A)VANCED PILOTS VERTICAL DIS'LAY TECHNIQUES

CONTRACT NO. N62269-71-C-05

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NORTHROP ELECTRONICS DIVISIO.I
PALOS VERDES PENINSULA, CALIFORNIA

JANUARY 1973

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13. ABSTRACT

This report summarizes the results of a one-year investigation of advanced vertical display techniques. The purpose of the study was to appraise the relative merits of nonconventional display techniques for their potential application aboard a 1985 era naval all-weather day/night attack aircraft. The vertical display system (VDS) must present situation, command, and multisensor (radar, FLIR and TV) information to the pilot and systems operator for aircraft flight control and mission functions. Mission requirements were defined including informative, functional and human factors, and VDS performance and design criteria were established. Two mission plans and scenarios were prepared to cover a wide range of aircraft flight conditions and weapon delivery modes to exercise the various avionics sensor systems and establish the worst case or most demanding VDS information and design requirements. A weighting factor tradeoff analysis was conducted using system parameter performance weighting factors determined by representatives of NADC to determine the capabilities of the 12 most promising non-CRT display techniques for fulfilling the VDS design requirements. Using weighting factors established by the Navy, the DIGISPLAY and liquid crystal display techniques were the most promising display techniques for the VDS applications. A tradeoff and cost-effectiveness analysis was conducted to determine the optimum scanning standards and the system design specifications for a complete VDS DIGISPLAY system. A preliminary design for the recommended VDS was prepared and a series of simulation tests were conducted to verify the performance and flyability of the recommended design.

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Candidate Display Techniques						

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AN INVESTIGATION OF ADVANCED PILOTS VERTICAL DISPLAY TECHNIQUES

FINAL REPORT
JANUARY 1973
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FOREWORD

This document entitled "An Investigation of Advanced Pilots Vertical Display Techniques" is the final report prepared for the Naval Air Development Center (NADC) by Northrop Electronics Division, One Research Park, Palos Verdes Peninsula, California. This report documents the work performed under Contract N062269-71-C-0574 during the period 1 July 1971 to 31 July 1972. Northrop Electronics Division Control Number NORT 71-295-2 has been assigned to this report. This report was submitted by the author on 22 September 1972.

The contract is sponsored by the Instrument Techniques Section of NASC under the supervision of Mr. J. Wolin and Mr. R. Berthot. The program was administered by Mr. K. Priest and Mr. N. Douglas of NADC.

Mr. J. McDade was the contractor program manager. The other Northrop personnel contributing to this program included Miss P. DuPuis and Messrs. E. Ebright, F. Freeman, J. Gunther, R. Honzik, T. Noda, W. Richardson, and H. Shoulders.

ABSTRACT

This report summarizes the results of a one-year investigation of advanced pilots vertical display techniques. The purpose of the study was to appraise the relative merits of nonconventional display techniques for 1985 era, all-weather, naval attack aircraft. The vertical display system (VDS) must present situation, command, and multisensor (radar, FLIR and TV) information to the pilot and systems operator for aircraft flight control and mission functions. Mission requirements were established which, in turn, defined the information content, functional and human factors performance criteria for the VDS. Two mission plans and scenarios were prepared to cover a wide range of aircraft flight conditions and weapon delivery modes to exercise the various avionics sensor systems and establish the worst-case or most demanding VDS information and design requirements. A weighting factor tradeoff analysis was conducted using system parameter performance weighting factors selected by representatives of NADC to determine the capabilities of the twelve most promising nonconventional display techniques for fulfilling the VDS design requirements. Using weighting factors established by the Navy, the DIGISPLAY and liquid crystal display techniques were the most promising display techniques for the VDS applications. A tradeoff and cost-effectiveness analysis was conducted to determine the optimum scanning standards and the system design specifications for a complete VDS DIGISPLAY system. The results of this study indicated that the 875 TV line scanning standard with eight shades of gray scale was the optimum choice, because it offered the highest performance per unit cost of all the systems analyzed, and hence was considered the most cost-effective. A preliminary design was prepared for the optimum VDS, and a series of simulation tests were conducted to verify the performance and flyability of the recommended design.

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CONTENTS (Continued)

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

LIST OF TABLES (Cont'd)

1.0 INTRODUCTION AND SUMMARY

This final report summarizes the results of a one-year investigation of advanced vertical display techniques performed under U.S. Navy Contract N062269-71-C-0574. The purpose of the study was to appraise the relative merits of nonconventional display techniques for their potential application in an advanced multisensor vertical display system (VDS) for use in a 1985 era naval all-weather, day/night attack aircraft. The aircraft will be a two-place (tandem cockpit arrangement), post-F-14 design with top speed of Mach 3.0 and be capable of supersonic dash at Mach 1.2 at sea level for radar penetration purposes. The vertical display system must present situation, command, and (or) multisensor (radar, FLIR and TV) information to the pilot and systems operator for aircraft flight control and mission functions.

The study was conducted in three parts. The first part defined the total mission requirements, including information, functional, and human factors requirements, and established vertical display system performance and design criteria based on the anticipated aircraft avionics systems and weapon capabilities that will be available in the 1985 era. Two mission plans and scenarios were prepared in order to cover a wide range of aircraft flight conditions and weapon delivery modes to exercise the various avionics sensor systems and establish the worst case or most demanding VDS information and design requirements. Functional flow diagrams were prepared for the pilot and systems operator stations from which the essential information requirements were determined and allocated to the various onboard cockpit display systems. The VDS display content was developed and compared with other display systems on presently operational aircraft, and a series of display formats were synthesized with a VDS mode of operation designed to cover each flight phase of the aircraft.

The VDS performance objectives and design goals were determined by analyzing the worst case imaging requirements of the high-resolution multisensor avionics system contemplated for use in the 1985 era. This included such sensor systems as low-light-level television, high-resolution vidicons, forward-looking infrared (FLIR) and multiple mode radar systems. A modulation transfer analysis and signal-to-noise analysis were performed to determine the

most important parameters for the dot matrix display such as resolution, contrast, shades of gray, and number of scanning lines required to be compatible with the anticipated levels of performance expected from the complete sensor system. The modulation transfer characteristics of a digitally scanned dot matrix display system were derived and compared with the continuously scanned case, and the human factors requirements were determined including display brightness, refresh rate, symbol size and font.

During the second part of the study, a weighting factor analysis was conducted to determine the capabilities and limitations of the various advanced non-CRT candidate display techniques in regard to their potential fulfillment of the VDS design and performance goals previously established. A literature survey was conducted and the most recent performance data and display technical information was requested from 25 of the leading commercial companies involved in extensive research and development programs in the various display technology areas of interest. This information was compiled, analyzed and estimates made of future (1975) system performance based on the levels of performance achieved to date. This data was analyzed and evaluated using a series of weighting factor assignments (allocated by representatives of NADC) to 24 of the most important display characteristics and performance parameters. The weighting factors were formulated for the purpose of evaluating and comparing the capabilities of the various non-CRT techniques regarding their potential application to the 1985 VDS. These characteristics and performance parameters were selected as a result of studies which indicated that they would have a direct effect on the performance of the video system, and could be used as guidelines to the eventual determination of whether the candidate display techniques could achieve the level of performance required for an operational VDS. The results of the weighting factor analysis enabled the relative ranking and narrowing of the total of 12 candidate display techniques down to the five most promising. These five techniques (including DIGISPLAY, liquid crystal, ferroelectric, LEDs, and A.C. plasma) considered to be the most attractive candidates for the VDS application were then studied in detail with respect to the systems reliability considerations, and a final ranking of the top five candidates was performed.

The DIGISPLAY and liquid crystal techniques received the highest scores in the analysis using Navy weighting factors, and were therefore considered as the most attractive candidates for the future VDS. It was decided to use the DIGISPLAY for the preliminary design analysis because of Northrop's familiarity and experience with the technique, and because it had received the highest weighting factor score.

The third part of the study conducted a preliminary design tradeoff and cost-effectiveness analysis to determine the optimum operational and design parameters for a DIGISPLAY VDS. Scanning standards of 875, 945, and 1023 TV lines were considered with eight and ten shades of gray scale capability. This study concluded that the 875 TV line scanning standard with eight shades of gray was the most cost-effective system design for the VDS application. A preliminary design analysis of this system was performed to determine the preliminary specifications for the complete system including the display, computer, scan converter, symbol generator, and interface electronics.

A simulation program was also conducted during the third part of the study to obtain diagnostic measurements of a simulated dot matrix display in comparison with a conventional raster scanned CRT and to determine the relative merits of the 875, 945, and 1023 TV line scanning standards. A dynamic simulation of the proposed VDS dot matrix formats for takeoff/cruise and landing modes was conducted to evaluate and obtain system design and human factors information regarding optimum font, size and spatial grouping of symbols, the placement, movement patterns and contents of the information, and the adaptability of the pilots and systems operators for conversion from the existing cockpit displays to the proposed new VDS.

REPORT SUMMARY

The report is organized into three parts. Part one consists of sections 1 and 2 which are concerned with the establishment of the preliminary design goals of the VDS. Included in Section 1 of this report are the mission plans, scenarios, and the functional flow diagrams associated with the proposed missions. The information requirements and display content are analyzed, and the suggested formats for the various VDS display modes are presented.

Section 2 contains an MTF analysis of the worst case-imaging requirements for the various avionics sensor systems carried on board the attack aircraft. The human factors requirements are discussed and the VDS performance criteria and design objectives are established.

The second part of the report contains sections 3 through 7, which are concerned with the selection of the optimum display techniques for the VDS application.

Section 3 discusses the derivation of the weighting factors from the VDS design goals. Section 4 presents a short technology assessment of the various display technologies. Section 5 discusses the results of the weighting-factor analysis and presents the relative ranking of the candidate display techniques. Section 6 analyzes the system reliability considerations of the five most promising display techniques. Section 7 contains the conclusions and recommendations of the display techniques study.

The third part of the report consists of sections 8 through 11 which are concerned with the selection of the optimum design parameters for the VDS. Section 8 discusses the results of the diagnostic and dynamic format simulation programs. Section 9 contains a trade-off analysis of 875, 945, and 1023 TV line VDS DIGISPLAY systems. Section 10 is a cost-effectiveness analysis of the optimum system parameters for the VDS application, and section 11 presents a preliminary design analysis of the proposed VDS system.

The appendices contain supporting technical information that is pertinent to the study results. Appendix A1 contains the derivation of the MTF characteristics of a digitally-scanned dot matrix system and compares the performance with a continuously scanned system. Appendix A2 contains the detailed scoring sheets for the weighting factor analysis. Appendix A3 describes the principles of operation of a storage DIGISPLAY system. Appendices A4, A5, and A6 provide detailed calculations of the capacitance parameter values for the switching plates of the DIGISPLAY systems that were studied, and Appendix A7 calculates the phosphor life versus brightness for the recommended DIGISPLAY systems.

1.1 STUDY METHODOLOGY AND SYSTEM PARAMETERS

Sections 1.1 through 1.9 of this report contain the results of the Requirements Analysis conducted by Northrop Human Factors/System Analysis personnel. There analyses provided the baseline data and Human Factors requirements for the Vertical Display System (VDS) study.

The purpose of this effort was to determine what information should be displayed, and the optimum formats for its presentation on the integrated VDS for either the pilot, the system operator (or both) during the conduct of various attack missions during the 1985 time frame.

A systematic approach was implemented during the first phase of this study to develop firm base lines, hypotheses and constructs required for the projection of future mission-oriented requirements. Two primary ground rules were exercised throughout the sequential development of the Human Factors analyses. First, the information required would be identified at the appropriate level for each specific mission phase, segment, or task. Secondly, the aircraft on-board systems and weapon/delivery modes would be based on conservative estimates of future system and subsystem development.

The Requirements Analysis consisted of three major areas. These analyses included the definition of Mission Requirements, the identification of Information Requirements and the determination of Display Content. The following tasks were accomplished and are discussed in detail in subsections 1.1 through 1.9.

a. Establish mission/sensor/weapon parameters for the required time frame.

b. Determine sensor or sensor combinations used for accomplishment of specific mission, or mission segment objectives.

c. Determine attack missions and mission parameters, and prepare scenarios for specified missions.

d. Prepare Functional Flow Diagrams for selected missions, and allocate functions to pilot and/or system operator positions.

e. Develop Information Requirements (IR) based on identified mission functions, and allocate the information displayed to the integrated VDS, or to other functional control/display areas at each crew station.

f. Determine VDS information content and compare with existing VSD system(s) display content.

g. Develop Control/Display Requirements, including display format, symbology, presentation mode, etc. Emphasis will be directed toward military standardization requirements for this type of displayed information.

h. Prepare recommended VDS formats for selected mission phases.

To obtain a realistic baseline for the information requirements of the air crew for successful completion of the selected attack missions, the following variables were analyzed: parameters of a 1985 attack aircraft; probable onboard sensor systems; and the probable types of weapons which will be delivered in the operational time frame. The aircraft, sensors and weapon delivery modes were based on a conservative projection of subsystem capabilities for the 1985 time period. The projected subsystems hypothesized may be more efficient, reliable, automatic, etc., than the existing operational systems, but they will be required to operate in the same environments, by the same types of personnel, and the sensor systems will be constrained to operate in the same spectral regions as presently existing systems.

1.1.1 Mission Parameters

To fully exercise and allocate the vertical display system requirements, missions were selected which required aircraft launch, penetration, attack and recovery during the worst case flight conditions. Low level penetration and withdrawal mission phases were selected for analysis, as these flight regimes require more information to be displayed at one time than high level cruise to and from the target area.

For the purposes of examining the effects of automation on the pilot's and system operator's information requirements, two levels - or degrees - of man/machine system automation were investigated for the takeoff, cruise, low-level penetration and recovery mission phases. Mission No. 1 was based on a semiautomatic man/machine system.[1] In this mode, the operator performs in series with the equipment as part of a closed loop system. Mission No. 2 was based on the aircraft system designed as an automatic system, where the

operator performs parallel operations. That is, the pilot's or system operator's roles are that of system or subsystem managers, with monitoring and fault correction as the primary system functions performed.

Section 1.2 details the factors and parameters used in the development of the Mission Scenarios.

1.1.2 Aircraft Parameters

The attack aircraft postulated for the 1985 time frame is a twin engine, two place (tandem) cockpit design with a primary air-to-ground weapon delivery capability and an effective air-to-air defensive capability. The aircraft is designed for conventional takeoff and landing, incorporates a variable sweep wing, and has air-to-air refueling capabilities. The aircraft is designed for a sustained speed of Mach 2.8 at optimum altitude with a temperature-limited dash capability of Mach 3.0. It is capable of sustained sea level flight at Mach 1.2 and (low-level) dash at Mach 1.5.

The aircraft incorporates a high level of automation, including a digital avionics system, integrated stores management/weapon delivery system, automated fire control system and a fully integrated control/display system at the pilot's and system operator's positions.

Both crew stations will contain a multisensor VDS which can present at least the information from two sensors simultaneously. The field of view (FOV) of each sensor would be designed to have the same azimuth and elevation coverage so that the individual sensor "picture" could be superimposed over another sensor picture at the same time. Wide angle or narrow angle FOVs would be selectable at each crew station.

The simultaneous presentation of information would be especially effective for target detection, identification and designation. For instance, radar and IR returns could be combined during target acquisition. The radar returns could be limited to present medium contrast terrain features in the target area while hot targets would be highlighted by the superpositioned IR returns. Depending upon the type of terrain, weather (snow covering, etc.) and target types, the IR and radar roles may be reversed so that the IR presents the background while the radar provides the target information.

1.1.3 Sensor Parameters

A working paper matrix was developed to compare existing sensor capabilities and limitations under varied operational conditions such as: "Day - clear, restricted, obscure; Night - clear, restricted, obscure," vs target type and present usage. The purpose of this task was to determine which sensors could be used singly to accomplish a mission phase objective, or what combination(s) of sensors could be used simultaneously for even greater efficiency in accomplishing such tasks as target acquisition and weapon employment. A second but equally important objective was to determine the potential information/content which could be displayed and the effect on the multipurpose VDS display requirements.

The on-board sensors considered in this study include:

Forward Looking Radar	-	FLR
Air Intercept Radar	-	AIR
Forward Looking Infrared	-	FLIR
Air Search Infrared	-	ASIR
Low Light Level TV	-	LLLTV
High Resolution TV	-	HRTV
Laser	-	LAS
Target Identification System Electro Optical	-	TISEO
Radar Homing and Warning	-	RHAW
Identification Friend or Foe (Secure Identification Feature)	-	IFF/SIF
Photo Camera	-	PC

1.1.4 Weapon(s)/Delivery Mode Parameters

The following types of weapons were considered in this study:

a. Air-to-Ground:

- Conventional bombs
- Nuclear weapons
- Standoff weapons
- Rockets
- Mines
- Torpedo

b. Air-to-Air:

Missiles (long range and dog-fight)

Cannon (20-30 mm)

1.1.5 Reconnaissance Sensors

The following types of reconnaissance sensors were considered:

Infrared (Line Scan)

Side-Looking Radar

Photo

Laser Camera

1.1.6 Tactical Systems

The tactical systems assumed to be operational in the 1985 time frame include:

a. Automatic Carrier Landing System - ACLS

The ACLS performs its primary function during darkness and weather and is activated on the final approach after the initial approach and the proper flight configuration have been established. The system provides the capability to automatically recover an aircraft on the carrier deck without pilot intervention. The Landing Signal Officer monitors the system operation and provides for manual override if "waveoff" action should be required.

b. Carrier Controlled Approach System - CCA

This system performs the function of establishing the initial conditions for handover to the ACLS and controls all aircraft entering the landing pattern. The CCA also provides the capability to perform the same functions as the ACLS would perform in a semiautomatic mode.

c. Combat Information Center - CIC

The CIC may be established on the carrier or as an Airborne CIC. The role of the CIC is to provide command and control of all launched aircraft in the assigned airspace subsequent to handover from departure control and until handover is made to the CCA for recovery. The CIC

also receives all strike information, provides control of air refueling areas and assignments, assists in rescue operations and provides pilot advisories.

d. Joint In-Flight Data Transmission System - JIFDATS

JIFDATS provides the capability to transmit sensor data (IR, SLAR, Photo, etc.) from an airborne reconnaissance aircraft directly (or via a relay aircraft) to a shipboard terminal for recording and viewing the data in near-real-time.

1.2 MISSION PROFILE AND SCENARIO DEVELOPMENT

The mission scenarios were developed for the purpose of conducting a comprehensive mission analysis and are based on Naval tactical doctrine applied to the hypothetical combat situations. Specifying the theater of operations was not considered essential in the development of the scenarios, since the missions described herein could be flown in many geographic locations. The missions described and the mission data generated can be applied to various types of Naval operations encompassing limited to full scale tactical situations.

Figure 1 depicts the mission parameters and first level functions selected to exercise the 1985 attack aircraft, on-board sensors and the Vertical Display System (VDS). The heavy flow line indicates the air-to-ground bomb attack and subsequent air-to-air defensive engagement hypothesized in Mission Scenario No. 1. The mission plan and overall flight profile from launch to recovery are also shown on this drawing.

Mission No. 2 includes a standoff weapon attack (Function 1.20) and a subsequent surface-to-air missile attack on the aircraft during the Escape Phase. First level functions 1.2 (Launch) through 1.5 (Penetrate) are identical to Mission No. 1, as are functions 1.13 (Cruise Back) through 1.15 (Recover Aircraft).

The factors considered in developing the specific mission requirements, mission plans, profiles, sensor and weapon selection, and operational procedures are as follows:

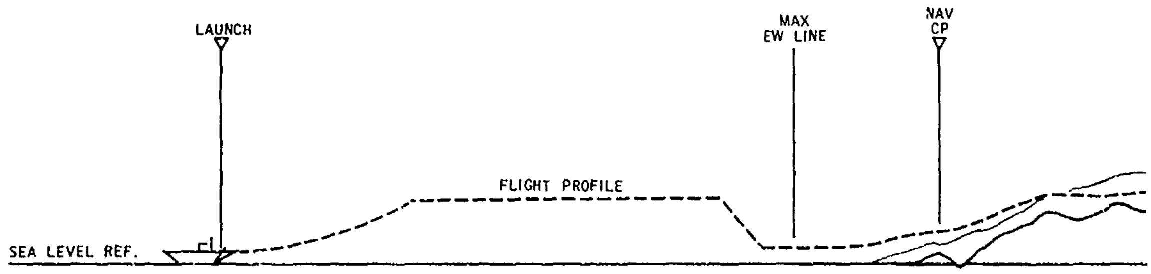
a. The scenarios to be based on realistic operational mission requirements involving launch and recovery from an attack carrier.

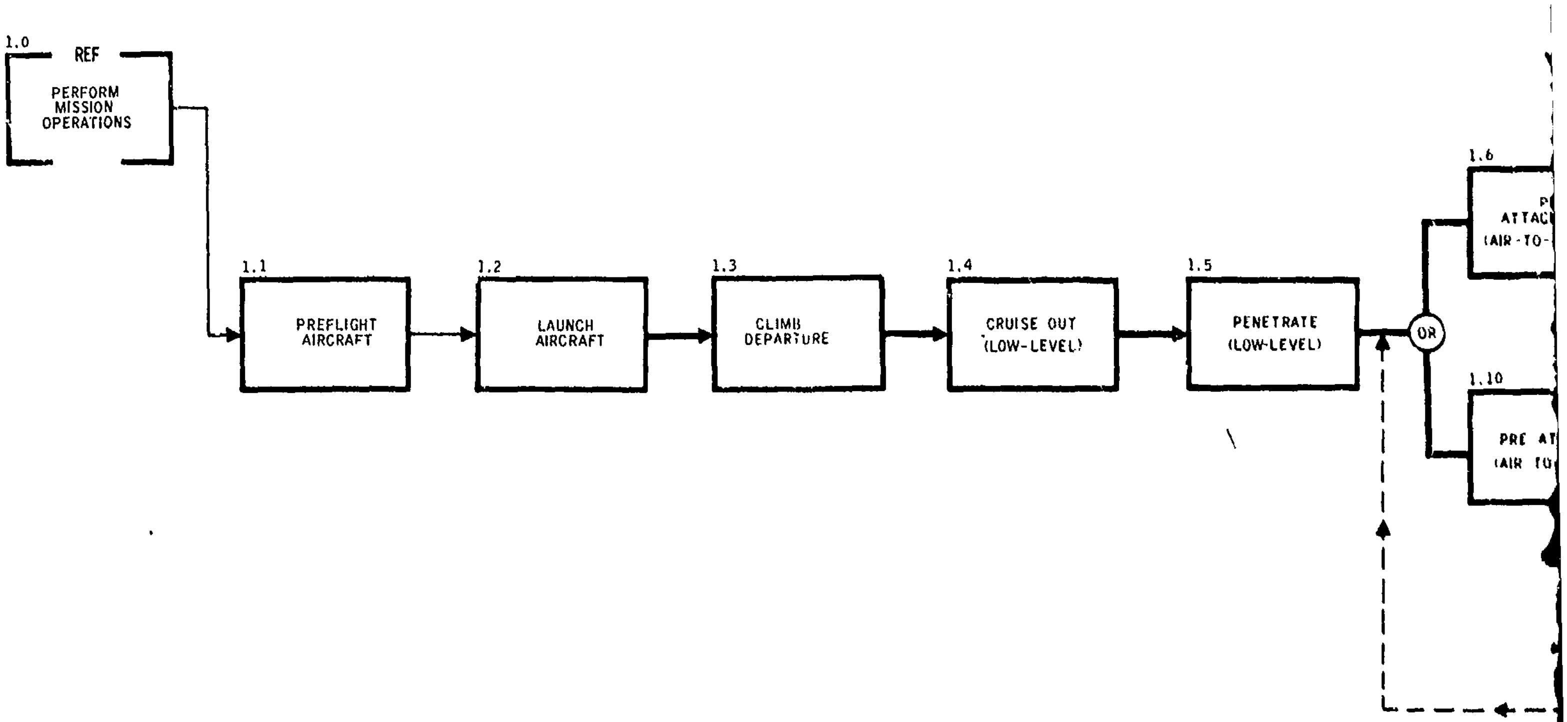
b. Target types which are typical of interdiction and counter-air missions.

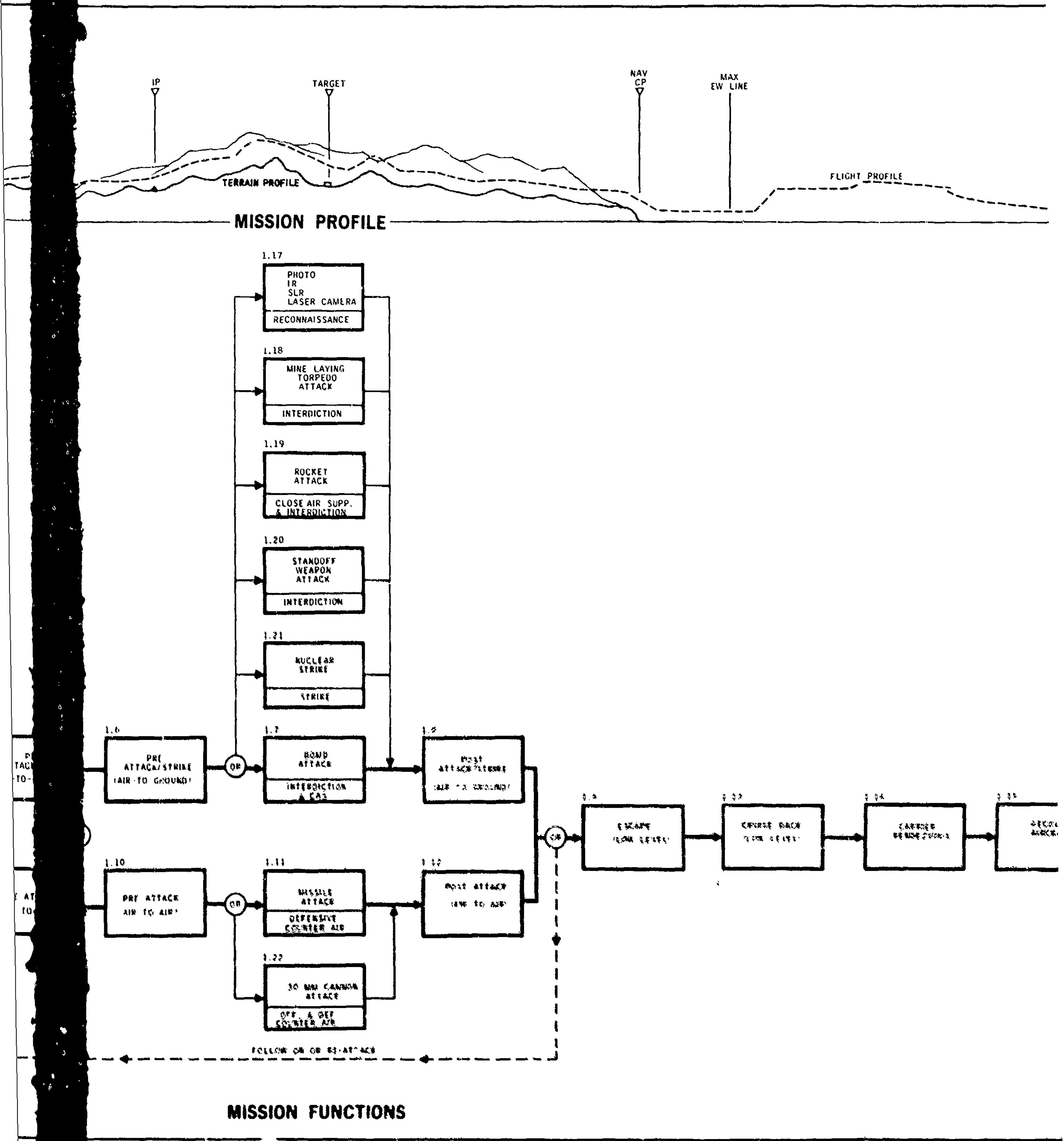
c. The target location and mission contingencies shall provide for exercising various realistic enroute and escape/recovery situations requiring different operational modes and displayed information.

d. The weapon(s) selected for delivery may exercise two or more sensors requiring different display characteristics.

e. Weather and time of day to be realistic and provide for exercising various types of sensors and displayed information.


LAUNCH
MAX EW LINE
NAV CP
FLIGHT PROFILE
SEA LEVEL REF.


1.0
REF
PERFORM MISSION OPERATIONS
1.1
PREFLIGHT AIRCRAFT
1.2
LAUNCH AIRCRAFT
1.3
CLIMB DEPARTURE
1.4
CRUISE OUT (LOW-LEVEL)
1.5
PENETRATE (LOW-LEVEL)
OR
1.6
1.10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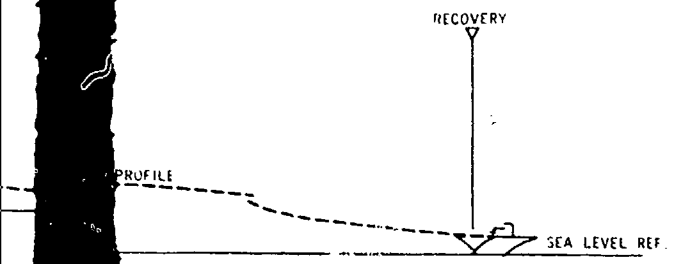
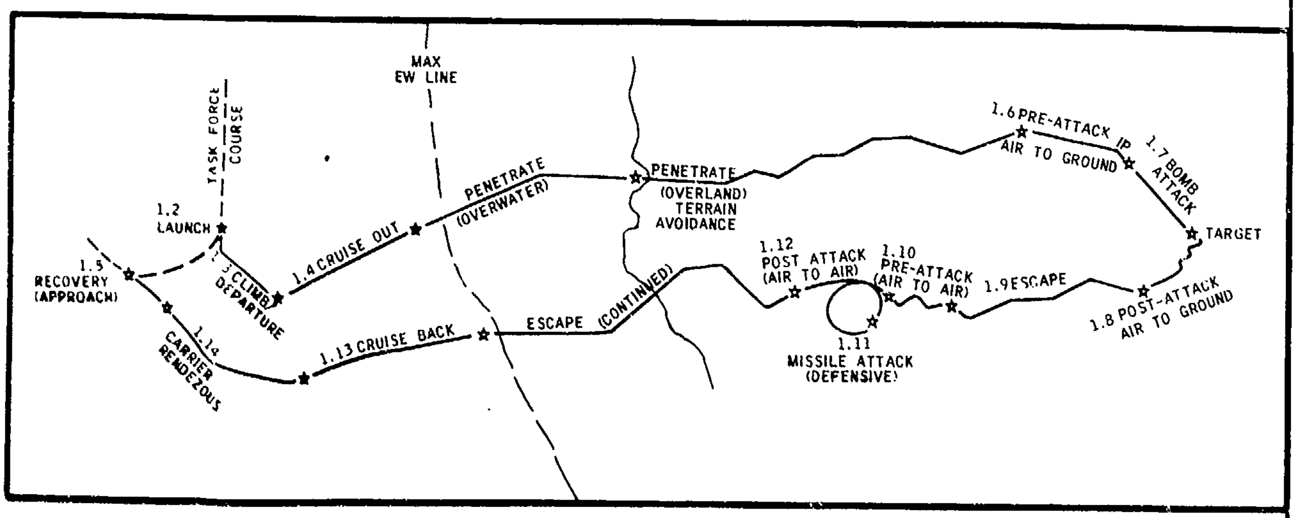
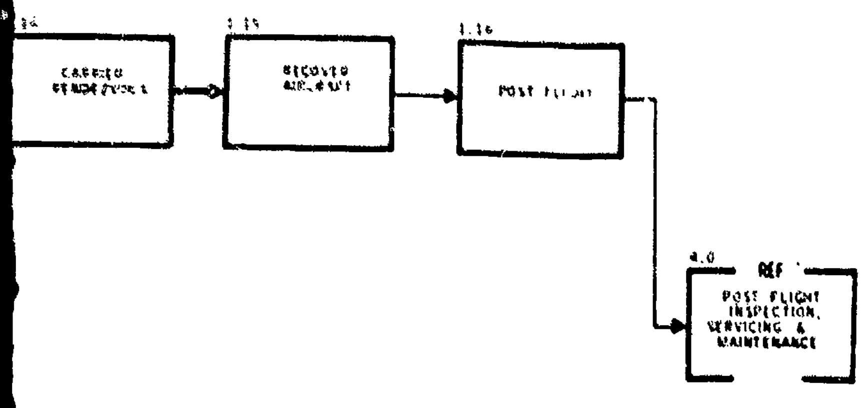
1.17
PHOTO
IR
SLR
LASER CAMERA
RECONNAISSANCE
1.18
MINE LAYING
TORPEDO
ATTACK
INTERDICTION
1.19
ROCKET
ATTACK
CLOSE AIR SUPP.
& INTERDICTION
1.20
STANDOFF
WEAPON
ATTACK
INTERDICTION
1.21
NUCLEAR
STRIKE
STRIKE
PRE
ATTACK/STRIKE
(AIR-TO-GROUND)
OR
BOMB
ATTACK
INTERDICTION
& CAS
POST
ATTACK/STRIKE
1.10
PRE ATTACK
AIR TO AIR
OR
1.11
MISSILE
ATTACK
DEFENSIVE
COUNTER AIR
POST ATTACK
(AIR TO AIR)
1.22
30 MM CANNON
ATTACK
OFF. & DEF
COUNTER AIR
FOLLOW ON OR RE-ATTACK
ESCAPE
(LOW LEVEL)
CRUISE BACK
(LOW LEVEL)
MISSION FUNCTIONS





MISSION PLAN



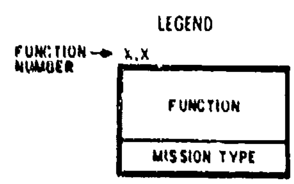


FIGURE 1 FIRST LEVEL FUNCTIONAL FLOW FUNCTION 1.0 - MISSION OPERATIONS
1980 ATTACK AIRCRAFT SYSTEM

f. Aircraft and equipment capabilities and limitations as they affect the mission plan and profile.

The requirement to be able to isolate and identify critical operational functions requiring specific information to successfully complete a tactical maneuver or task were also introduced into the mission scenarios.

For each mission these factors were integrated into a plan, then transferred to a map which depicted various typical targets, defenses, terrain and postulated military activities. Based on previous tactical mission planning and operations and with reference to Naval doctrine, a mission plan was developed.

1.3 MISSION NO. 1 - EXECUTION DESCRIPTION

The first-level functions required for Mission No. 1 are further broken out to second-level functions depicted in Figure 2, sheets 1 and 2. The flight profile associated with each mission phase is shown above the applicable phase and associated functions. The vertical phantom lines indicate the scope of the individual first level functions and are referenced along the bottom of the drawings.

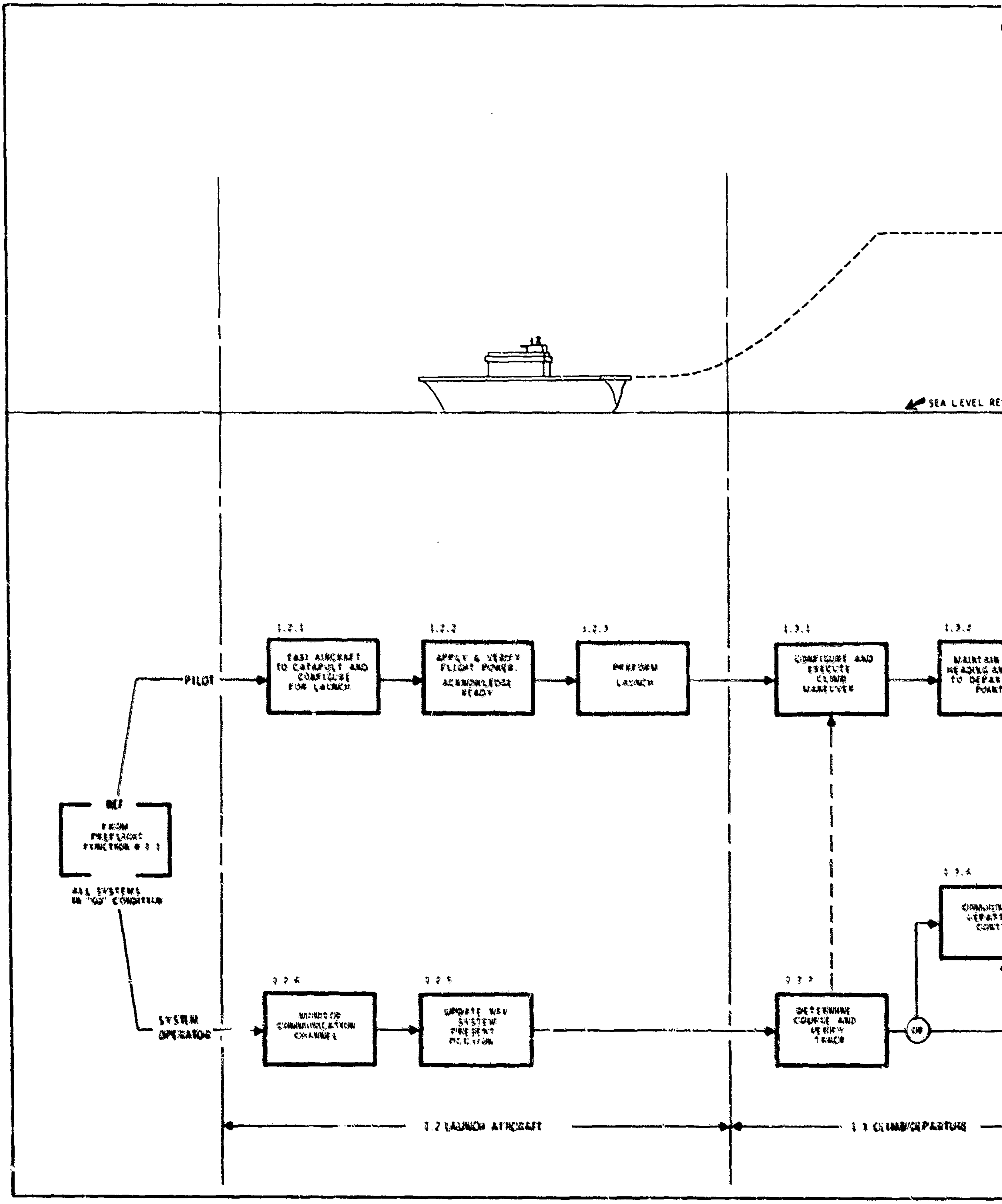
The first level functions, "Cruise Out" and "Penetrate," differ mainly in that during Cruise Out (or back) we assume that the aircraft is over friendly territory and not subject to surveillance or attack from the ground. During the Penetration phase, it is assumed that both electronic surveillance and the possibility of enemy ground-to-air and air-to-air attack can occur at any time. The Escape phase is similar to the Penetration phase in that the same conditions exist; i.e., the desirability of escaping detection and possible attack. In both the Cruise Out and Cruise Back phases, more emphasis can be placed on effective fuel management techniques, such as reduced airspeed and increased altitude, since the aircraft is beyond the enemy's early warning line.

The major mission phases prior and subsequent to the actual attack phase were selected to exercise VDS capabilities and assure that the pilot and/or system operator obtains necessary and sufficient information to successfully complete the hypothetical mission described in section 1.4.

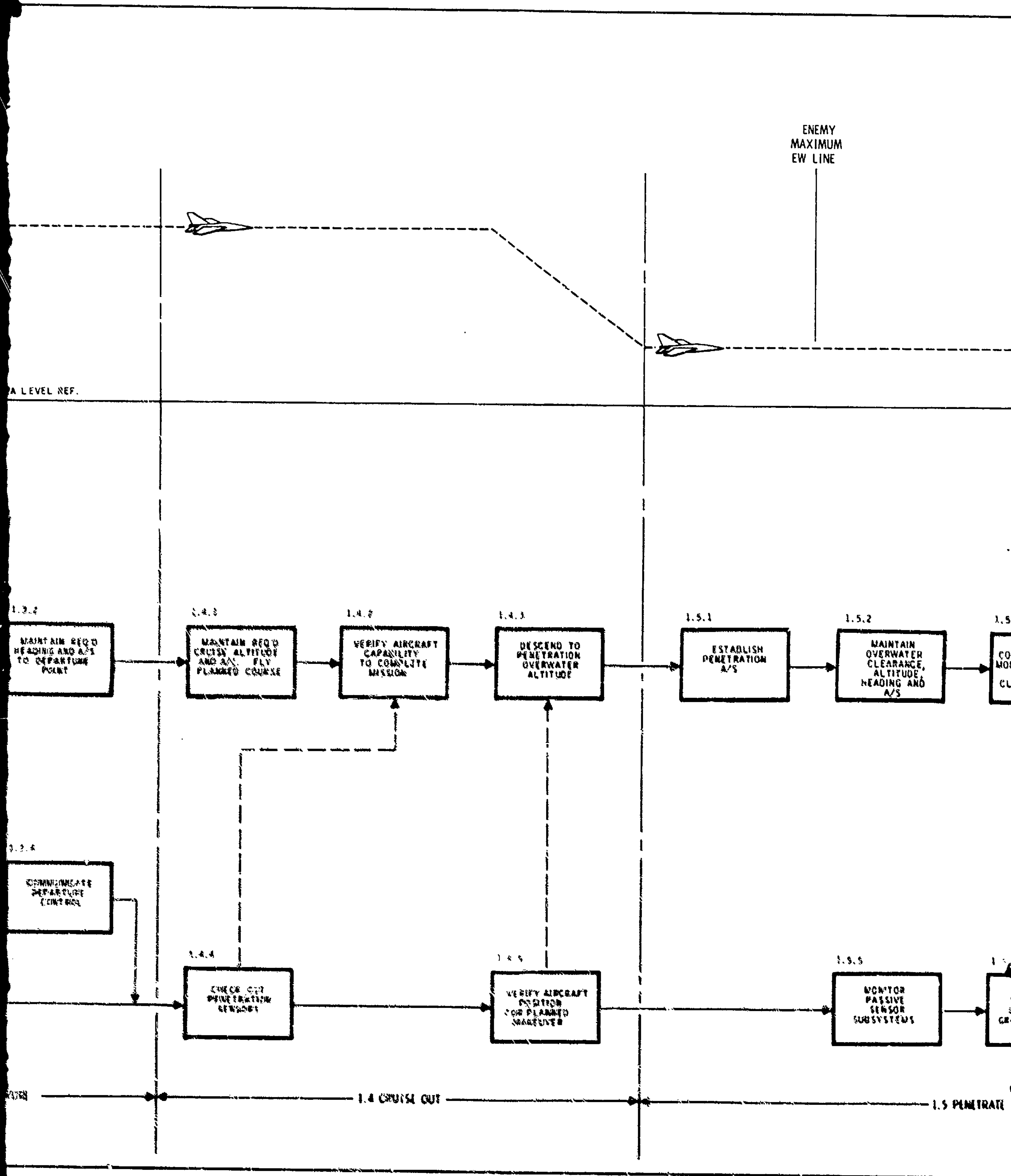
The air-to-air defensive engagement is an "unplanned event" following the bomb attack and occurs shortly after the attack aircraft has descended to the preplanned escape altitude. As depicted in Figure 2, sheet 2, the air-to-air pre-attack, attack and post-attack functions are offset from the preplanned mission events. After successfully completing the attack, the remainder of the Escape Phase (1.9) and subsequent mission phases are completed.

The following abbreviations used in the second level function flow block diagrams and mission scenarios include:

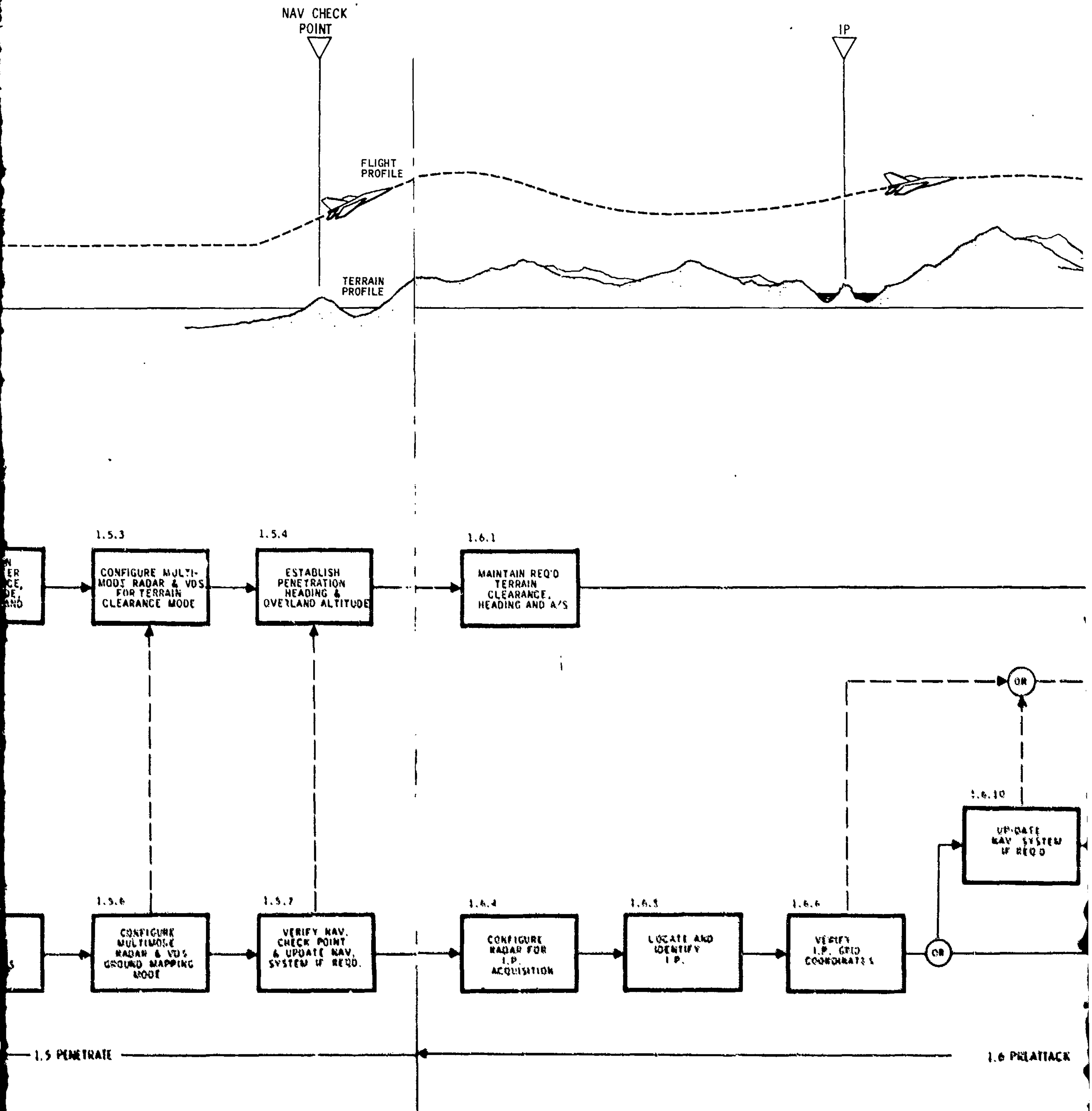
A/S - Airspeed
A/C - Aircraft
ATA - Actual Time of Arrival

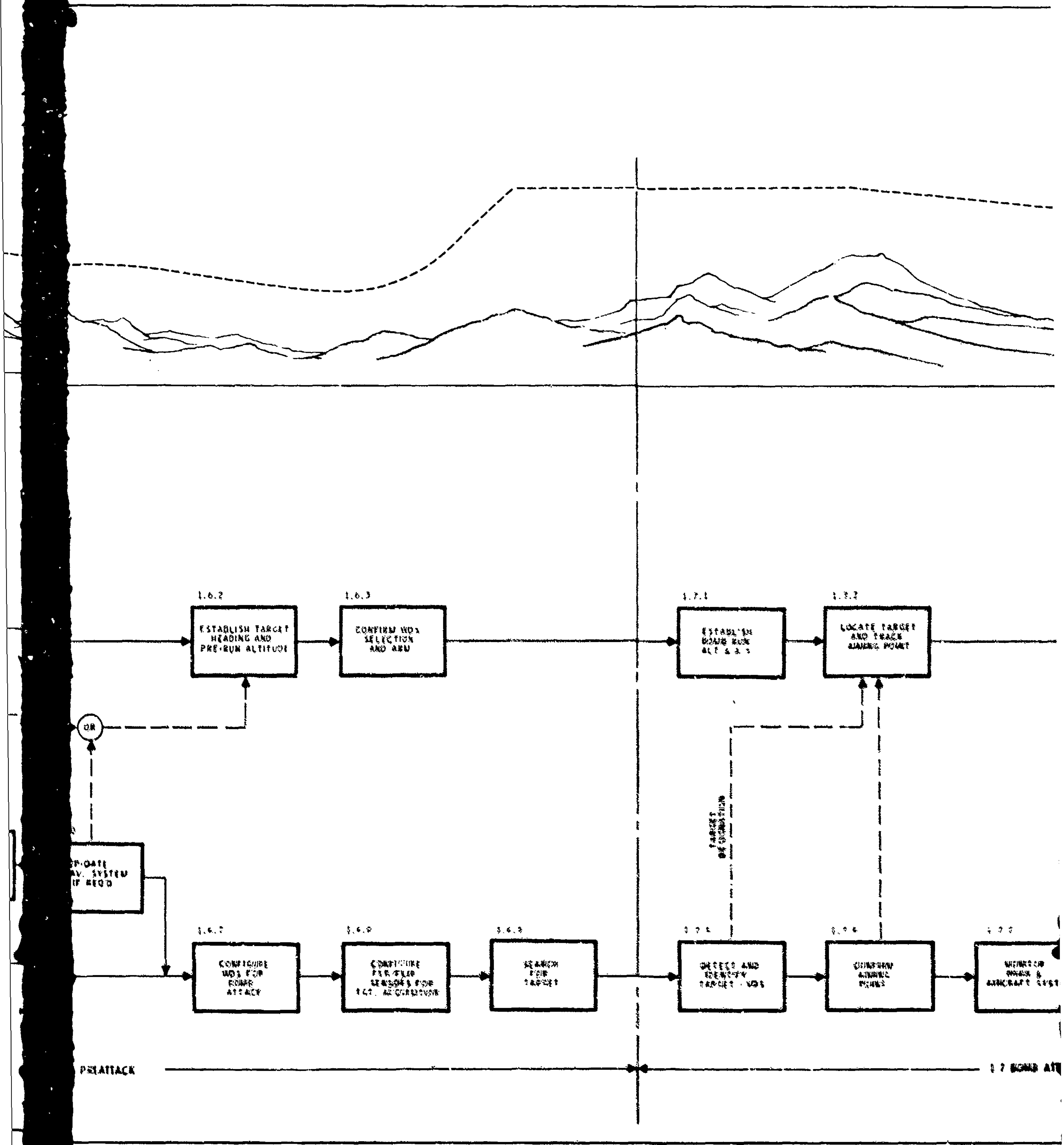


SEA LEVEL RE
PILOT
1.2.1
TAXI AIRCRAFT TO CATAPULT AND CONFIGURE FOR LAUNCH
1.2.2
1.2.3
1.3.1
1.3.2
ALL SYSTEMS IN "GO" CONDITION
UPDATE NAV SYSTEM



ENEMY
MAXIMUM
EW LINE
A LEVEL REF.
1.3.2
MAINTAIN REQ'D HEADING AND A/S TO DEPARTURE POINT
1.4.2
VERIFY AIRCRAFT CAPABILITY TO COMPLETE MISSION
DESCEND TO PENETRATION OVERWATER ALTITUDE
1.5.1
ESTABLISH PENETRATION A/S
1.5.2
MAINTAIN OVERWATER CLEARANCE, ALTITUDE, HEADING AND A/S
CHECK OUT PENETRATION SENSORS
VERIFY AIRCRAFT POSITION FOR PLANNED MANEUVER
1.5.5
MONITOR PASSIVE SENSOR SUBSYSTEMS
1.4 CRUISE OUT
1.5 PENETRATE


NAV CHECK POINT
IP
FLIGHT PROFILE
TERRAIN PROFILE
1.5.3
CONFIGURE MULTI-MODE RADAR & VDS FOR TERRAIN CLEARANCE MODE
1.5.4
ESTABLISH PENETRATION HEADING & OVERLAND ALTITUDE
1.6.1
MAINTAIN REQ'D TERRAIN CLEARANCE, HEADING AND A/S
OR
1.6.10
UP-DATE NAV SYSTEM IF REQ'D
1.5.6
CONFIGURE MULTIMODE RADAR & VDS GROUND MAPPING MODE
1.5.7
VERIFY NAV. CHECK POINT & UPDATE NAV. SYSTEM IF REQD.
1.6.4
CONFIGURE RADAR FOR I.P. ACQUISITION
1.6.5
LOCATE AND IDENTIFY I.P.
1.6.6
VERIFY I.P. GRID COORDINATES
OR
1.5 PENETRATE
1.6 PREATTACK


1.6.2
ESTABLISH TARGET HEADING AND PRE-RUN ALTITUDE
1.6.3
CONFIRM WDS SELECTION AND ARM
LOCATE TARGET AND TRACK
OR
AV. SYSTEM IF REQ'D
PREATTACK

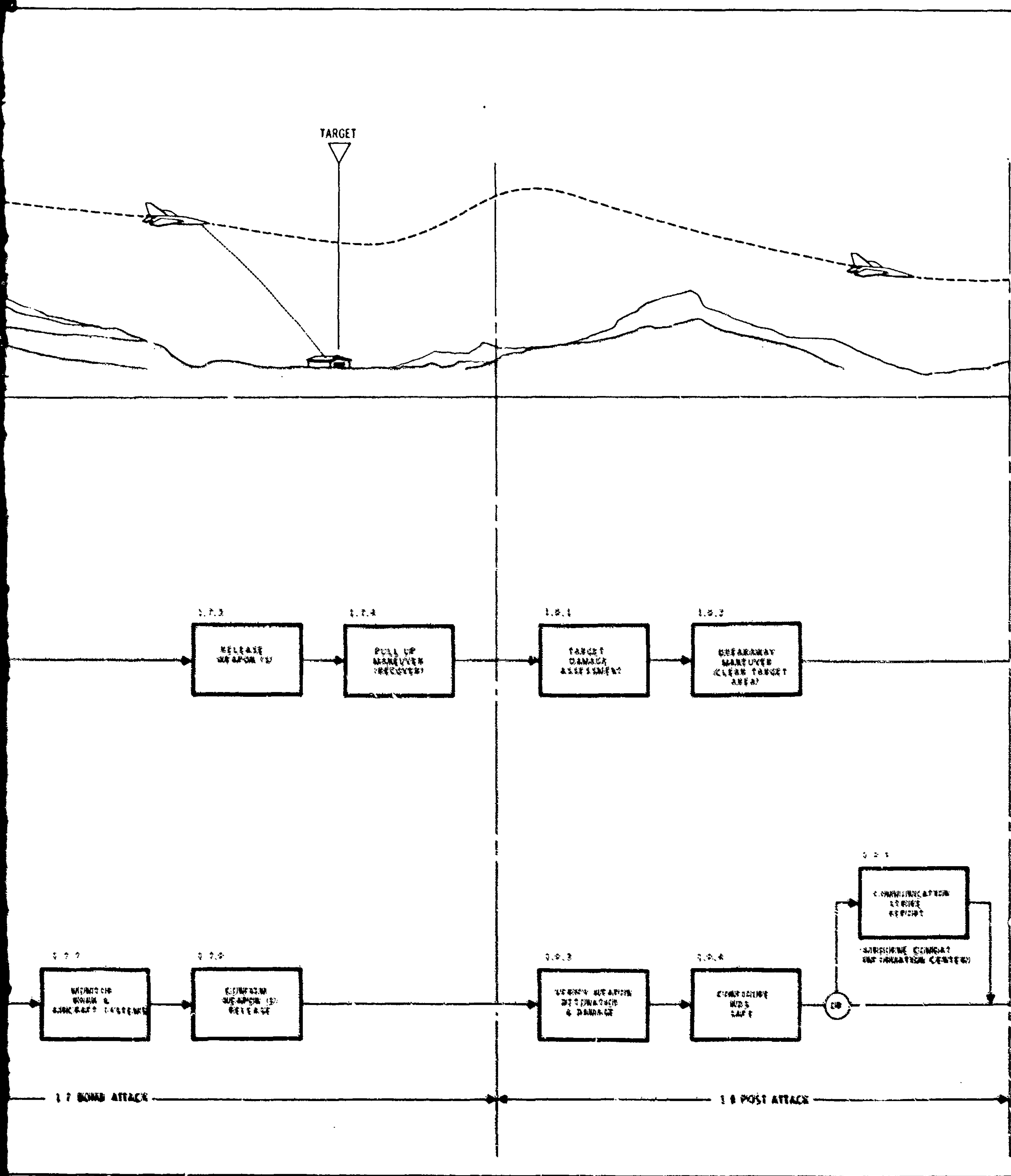
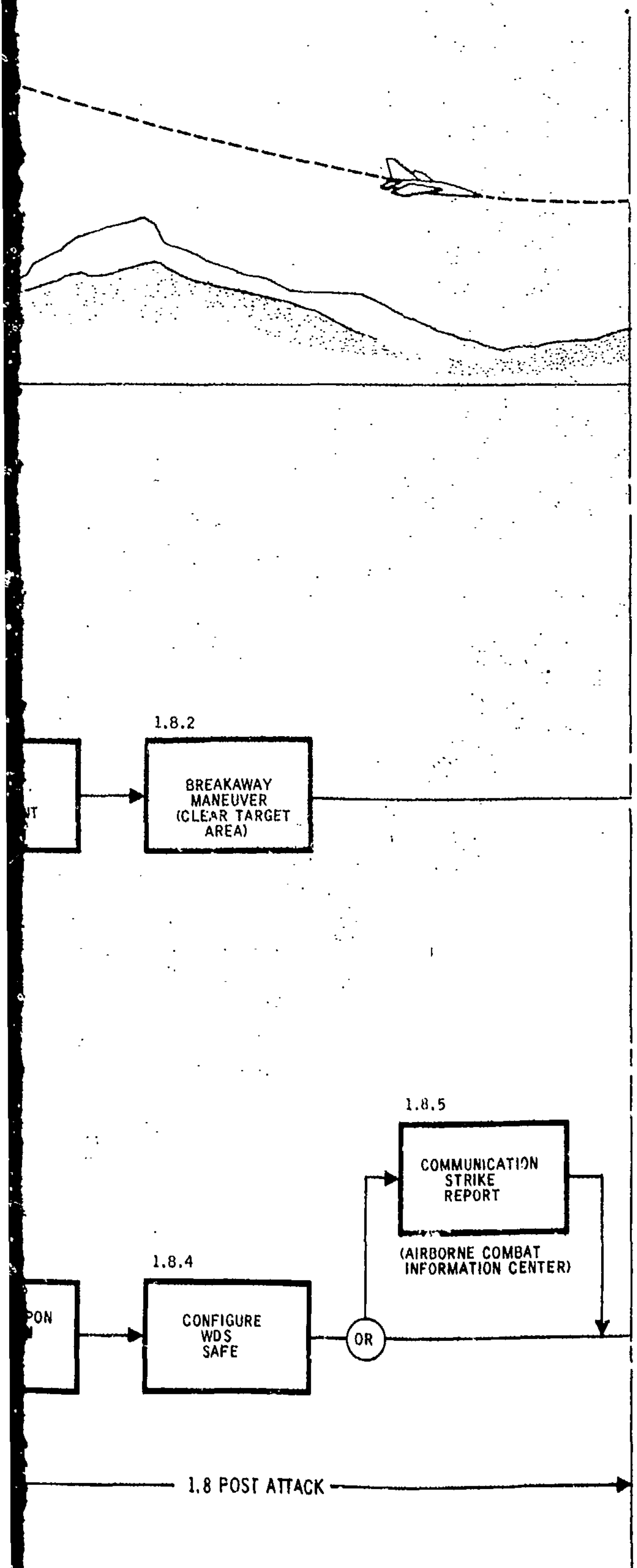


FIGURE 2 SECOND L
MISSION -



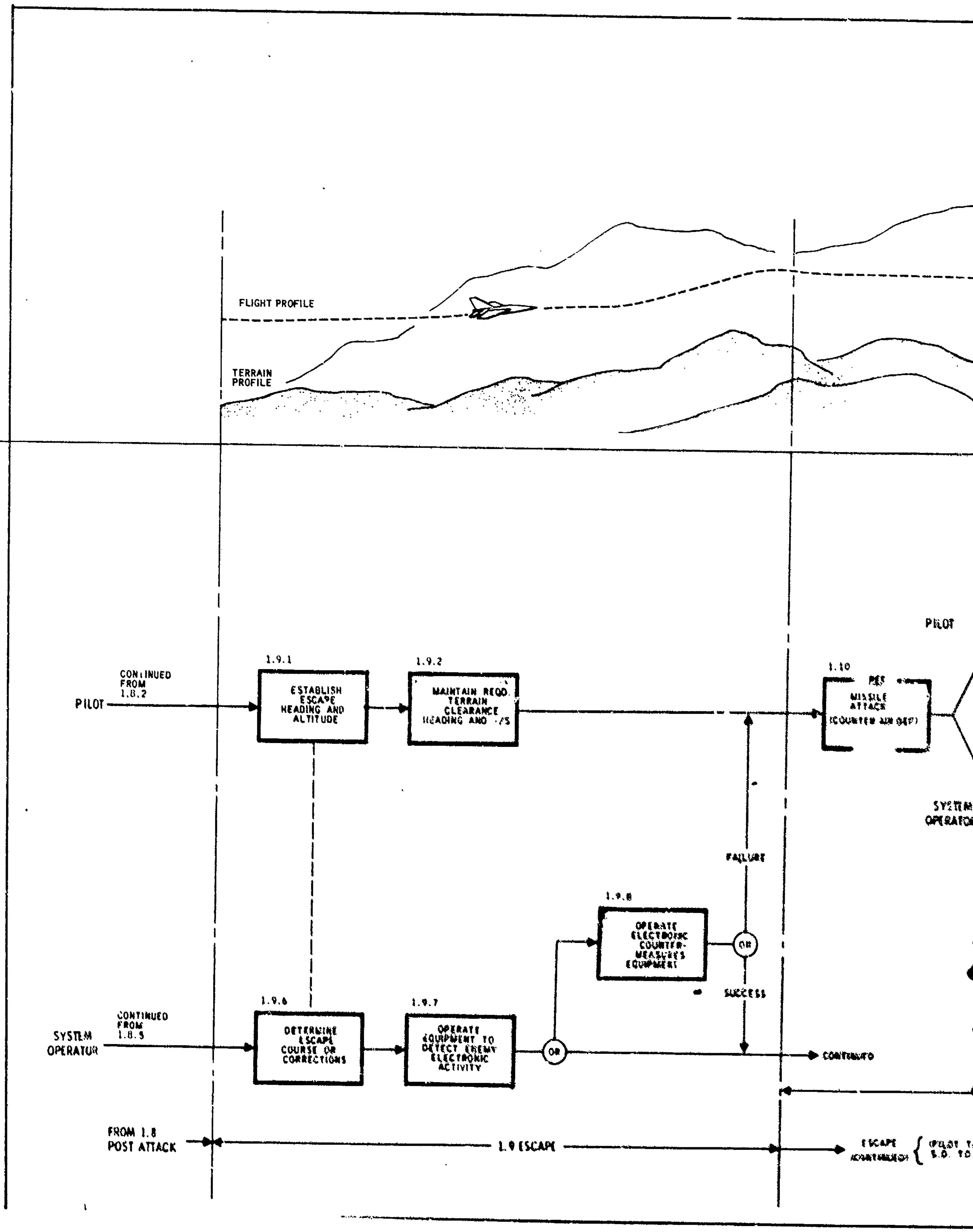
LEGEND

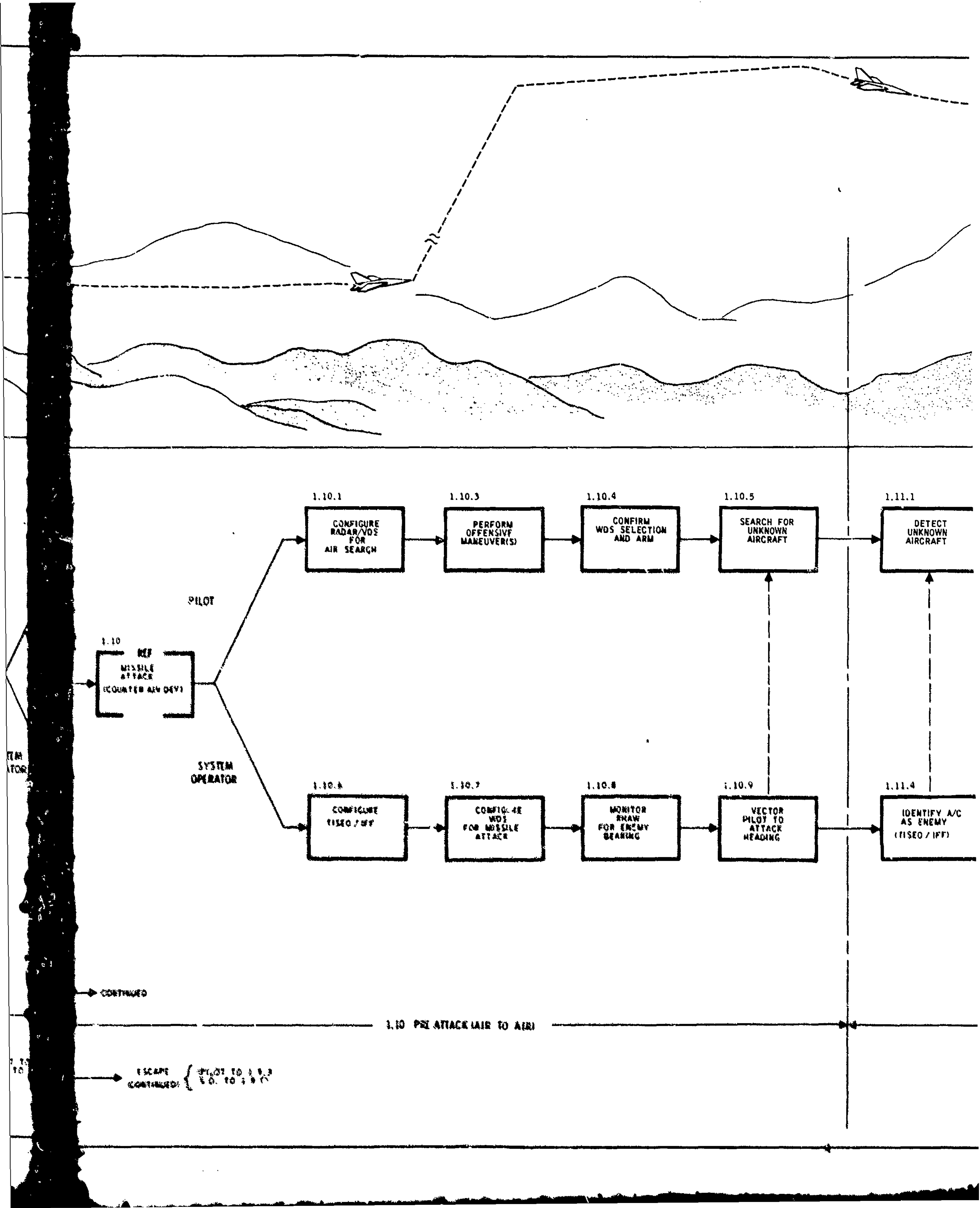
A/S	-	AIRSPEED
A/C	-	AIRCRAFT
FLIR	-	FORWARD LOOKING INFRARED SYSTEM
FLR	-	FORWARD LOOKING RADAR SYSTEM
IFF	-	IDENTIFICATION FRIEND OR FOE SYSTEM
IP	-	INITIAL POINT
RHAW	-	RADAR HOMING AND WARNING SYSTEM
TISEO	-	TARGET IDENTIFICATION SYSTEM, ELECTRO-OPTICAL
WDS	-	WEAPON DELIVERY SYSTEM
EW	-	EARLY WARNING

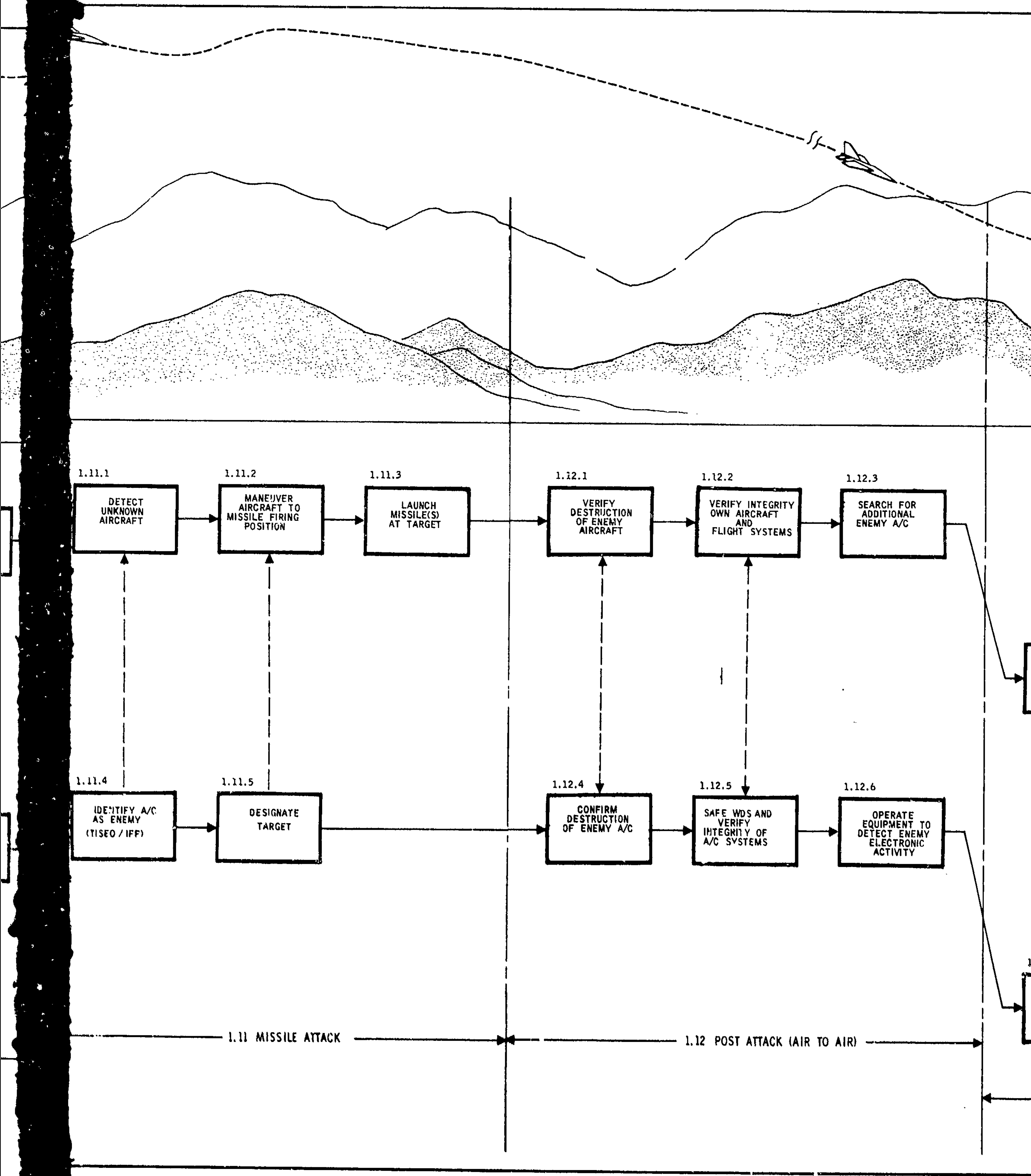
FUNCTION NUMBER → X.X.X.

FUNCTION

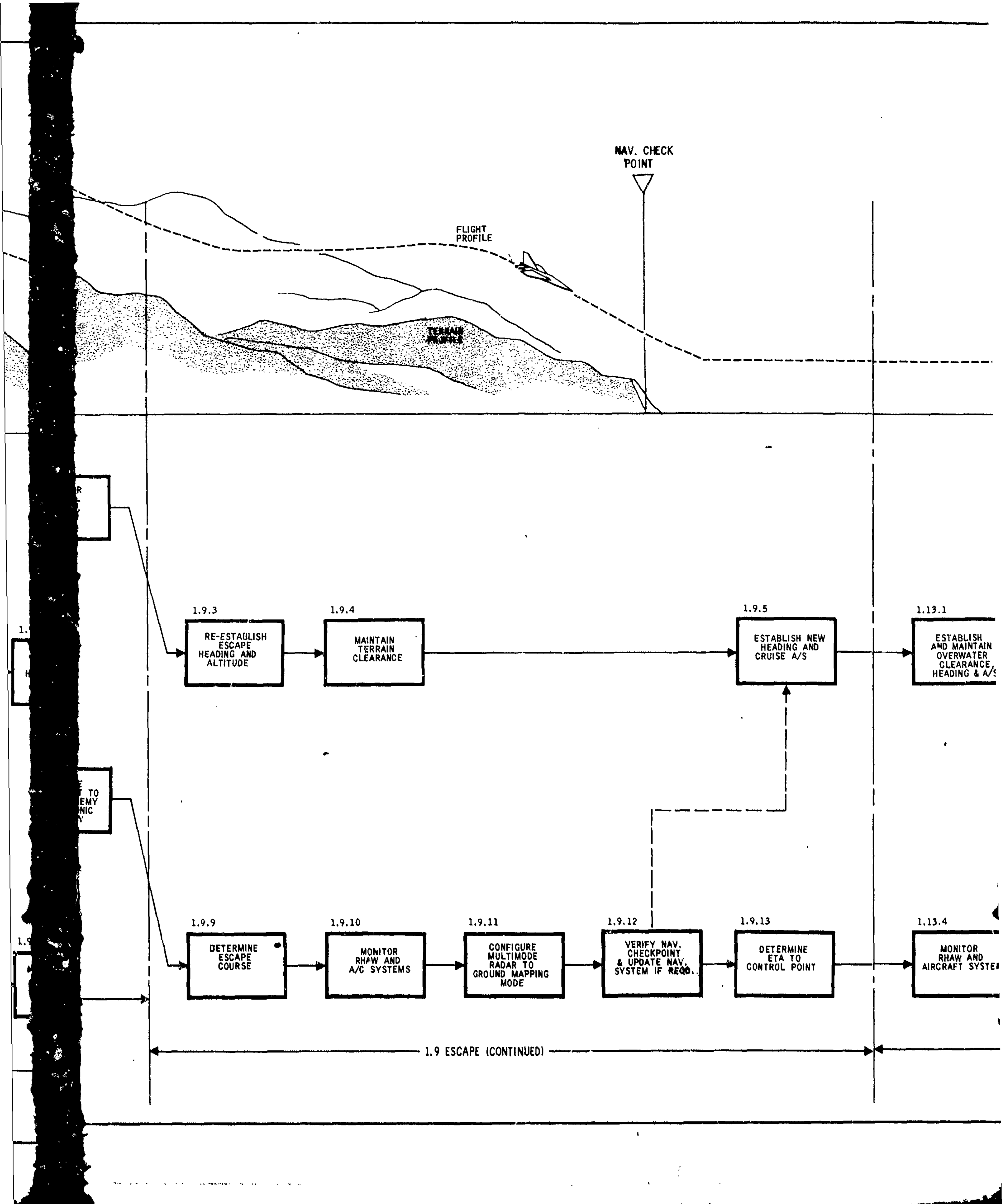
FIGURE 2 SECOND LEVEL FUNCTIONAL FLOW MISSION OPERATIONS - INTERDICTION MISSION - BOMB ATTACK (Sheet 1 of 2)

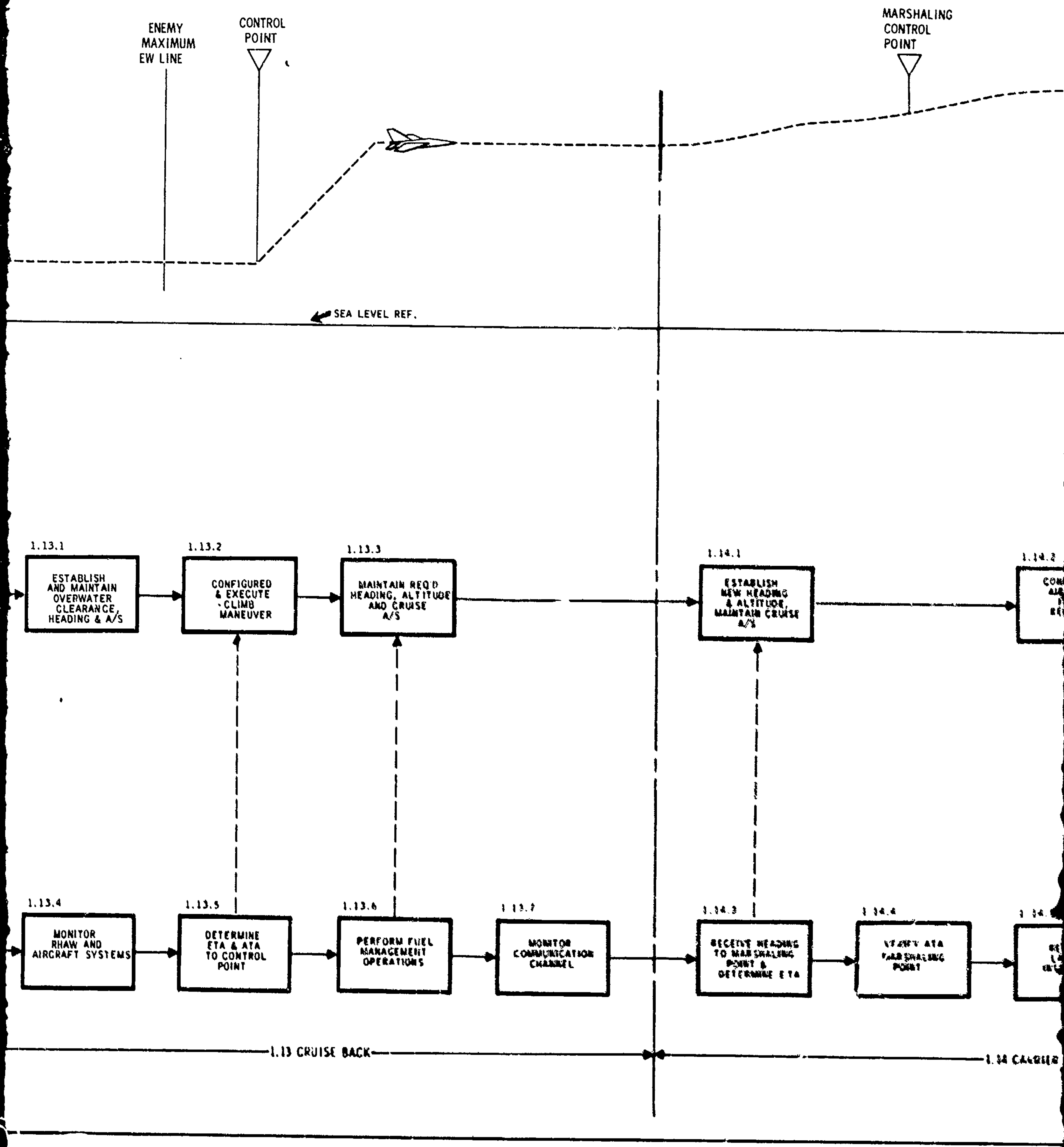

FLIGHT PROFILE
TERRAIN PROFILE
PILOT
CONTINUED FROM 1.8.2
1.9.1
ESTABLISH ESCAPE HEADING AND ALTITUDE
1.9.2
MAINTAIN REQD. TERRAIN CLEARANCE
1.10
MISSILE ATTACK
PILOT
SYSTEM OPERATOR
FAILURE
1.9.8
OPERATE ELECTRONIC COUNTER-MEASURES EQUIPMENT
OR
SUCCESS
SYSTEM OPERATOR
CONTINUED FROM 1.8.5
1.9.6
DETERMINE ESCAPE COURSE OR CORRECTIONS
1.9.7
OPERATE EQUIPMENT TO DETECT ENEMY ELECTRONIC ACTIVITY
OR
CONTINUED
FROM 1.8 POST ATTACK
1.9 ESCAPE
ESCAPE (CONTINUED)


1.10.1
CONFIGURE RADAR/WDS FOR AIR SEARCH
1.10.3
PERFORM OFFENSIVE MANEUVER(S)
1.10.4
CONFIRM WDS SELECTION AND ARM
1.10.5
SEARCH FOR UNKNOWN AIRCRAFT
1.11.1
DETECT UNKNOWN AIRCRAFT
PILOT
1.10
REF
MISSILE ATTACK
SYSTEM OPERATOR
1.10.6
CONFIGURE TISEO / IFF
1.10.7
CONFIGURE WDS FOR MISSILE ATTACK
1.10.8
MONITOR RHAW FOR ENEMY BEARING
1.10.9
VECTOR PILOT TO ATTACK HEADING
1.11.4
IDENTIFY A/C AS ENEMY (TISEO / IFF)
CONTINUED
1.10 PRE ATTACK (AIR TO AIR)
ESCAPE (CONTINUED)

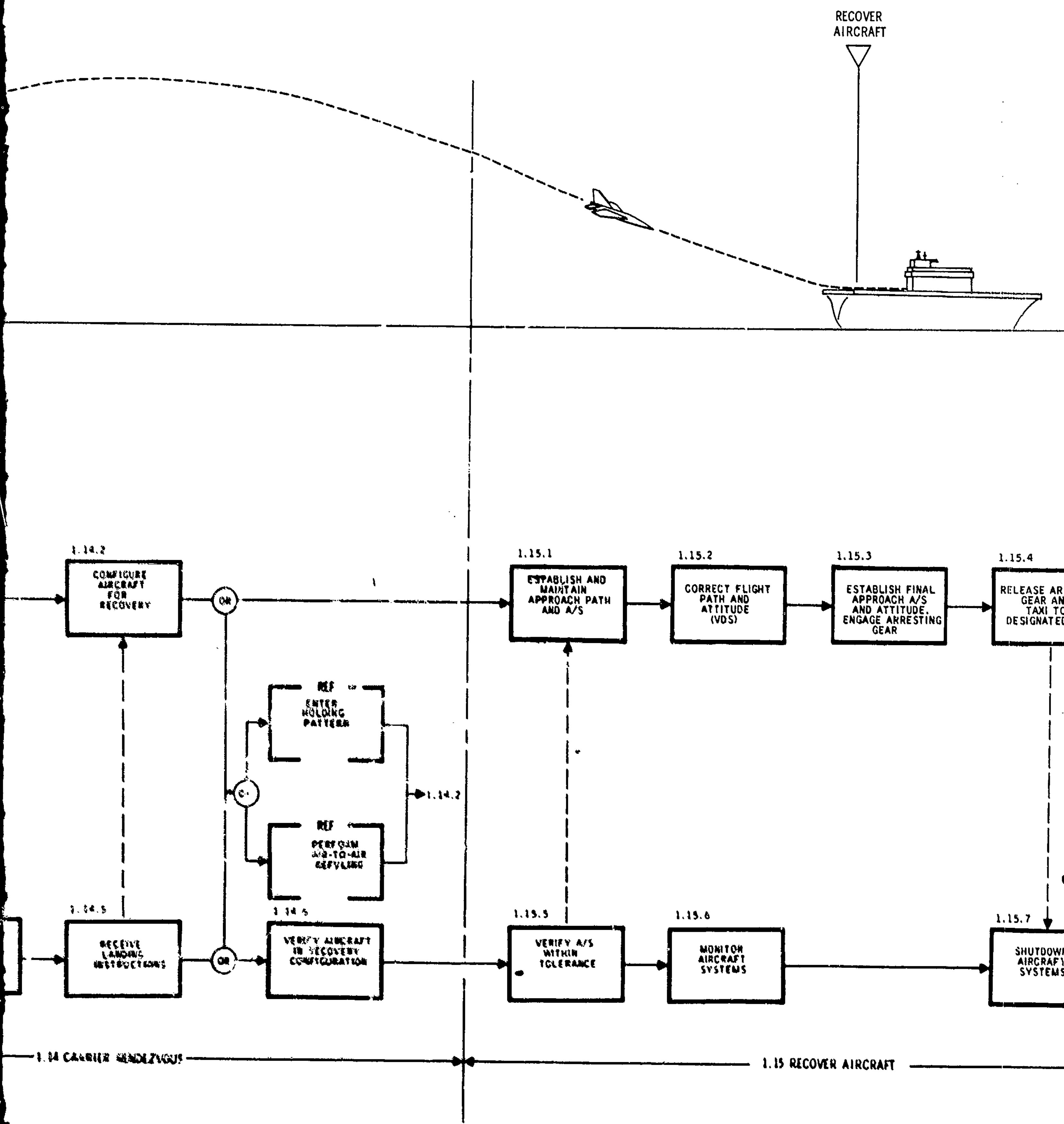


1.11.1
DETECT UNKNOWN AIRCRAFT
1.11.2
MANEUVER AIRCRAFT TO MISSILE FIRING POSITION
1.11.3
LAUNCH MISSILE(S) AT TARGET
1.12.1
VERIFY DESTRUCTION OF ENEMY AIRCRAFT
1.12.2
VERIFY INTEGRITY OWN AIRCRAFT AND FLIGHT SYSTEMS
1.12.3
SEARCH FOR ADDITIONAL ENEMY A/C
1.11.4
IDENTIFY A/C AS ENEMY (TISEO / IFF)
1.11.5
DESIGNATE TARGET
1.12.4
CONFIRM DESTRUCTION OF ENEMY A/C
1.12.5
SAFE WDS AND VERIFY INTEGRITY OF A/C SYSTEMS
1.12.6
OPERATE EQUIPMENT TO DETECT ENEMY ELECTRONIC ACTIVITY
1.11 MISSILE ATTACK
1.12 POST ATTACK (AIR TO AIR)


NAV. CHECK POINT
FLIGHT PROFILE
TERRAIN PROFILE
1.9.3
RE-ESTABLISH ESCAPE HEADING AND ALTITUDE
1.9.4
MAINTAIN TERRAIN CLEARANCE
1.9.5
ESTABLISH NEW HEADING AND CRUISE A/S
1.13.1
ESTABLISH AND MAINTAIN OVERWATER CLEARANCE, HEADING & A/S
1.9.9
DETERMINE ESCAPE COURSE
1.9.10
MONITOR RHAW AND A/C SYSTEMS
1.9.11
CONFIGURE MULTIMODE RADAR TO GROUND MAPPING MODE
1.9.12
VERIFY NAV. CHECKPOINT & UPDATE NAV. SYSTEM IF REQD.
1.9.13
DETERMINE ETA TO CONTROL POINT
1.13.4
MONITOR RHAW AND AIRCRAFT SYSTEMS
1.9 ESCAPE (CONTINUED)



ENEMY MAXIMUM EW LINE
CONTROL POINT
MARSHALING CONTROL POINT
SEA LEVEL REF.
1.13.1
ESTABLISH AND MAINTAIN OVERWATER CLEARANCE, HEADING & A/S
1.13.2
CONFIGURED & EXECUTE CLIMB MANEUVER
1.13.3
MAINTAIN REQ'D HEADING, ALTITUDE AND CRUISE A/S
1.14.1
ESTABLISH NEW HEADING & ALTITUDE, MAINTAIN CRUISE A/S
1.14.2
1.13.4
MONITOR RHAW AND AIRCRAFT SYSTEMS
1.13.5
DETERMINE ETA & ATA TO CONTROL POINT
1.13.6
PERFORM FUEL MANAGEMENT OPERATIONS
1.13.7
MONITOR COMMUNICATION CHANNEL
1.14.3
RECEIVE HEADING TO MARSHALING POINT & DETERMINE ETA
1.14.4
VERIFY ATA MARSHALING POINT
1.13 CRUISE BACK
1.14 CARRIER


RECOVER AIRCRAFT
1.14.2
CONFIGURE AIRCRAFT FOR RECOVERY
OR
REF
ENTER HOLDING PATTERN
REF
PERFORM AIR-TO-AIR REFUELING
1.14.2
1.14.5
RECEIVE LANDING INSTRUCTIONS
OR
VERIFY AIRCRAFT IN RECOVERY CONFIGURATION
1.15.1
ESTABLISH AND MAINTAIN APPROACH PATH AND A/S
1.15.2
CORRECT FLIGHT PATH AND ATTITUDE (VDS)
1.15.3
ESTABLISH FINAL APPROACH A/S AND ATTITUDE. ENGAGE ARRESTING GEAR
1.15.4
RELEASE AR GEAR AN TAXI TO DESIGNATED
1.15.5
VERIFY A/S WITHIN TOLERANCE
1.15.6
MONITOR AIRCRAFT SYSTEMS
1.15.7
SHUTDOWN AIRCRAFT SYSTEMS
1.14 CARRIER RENDEZVOUS
1.15 RECOVER AIRCRAFT

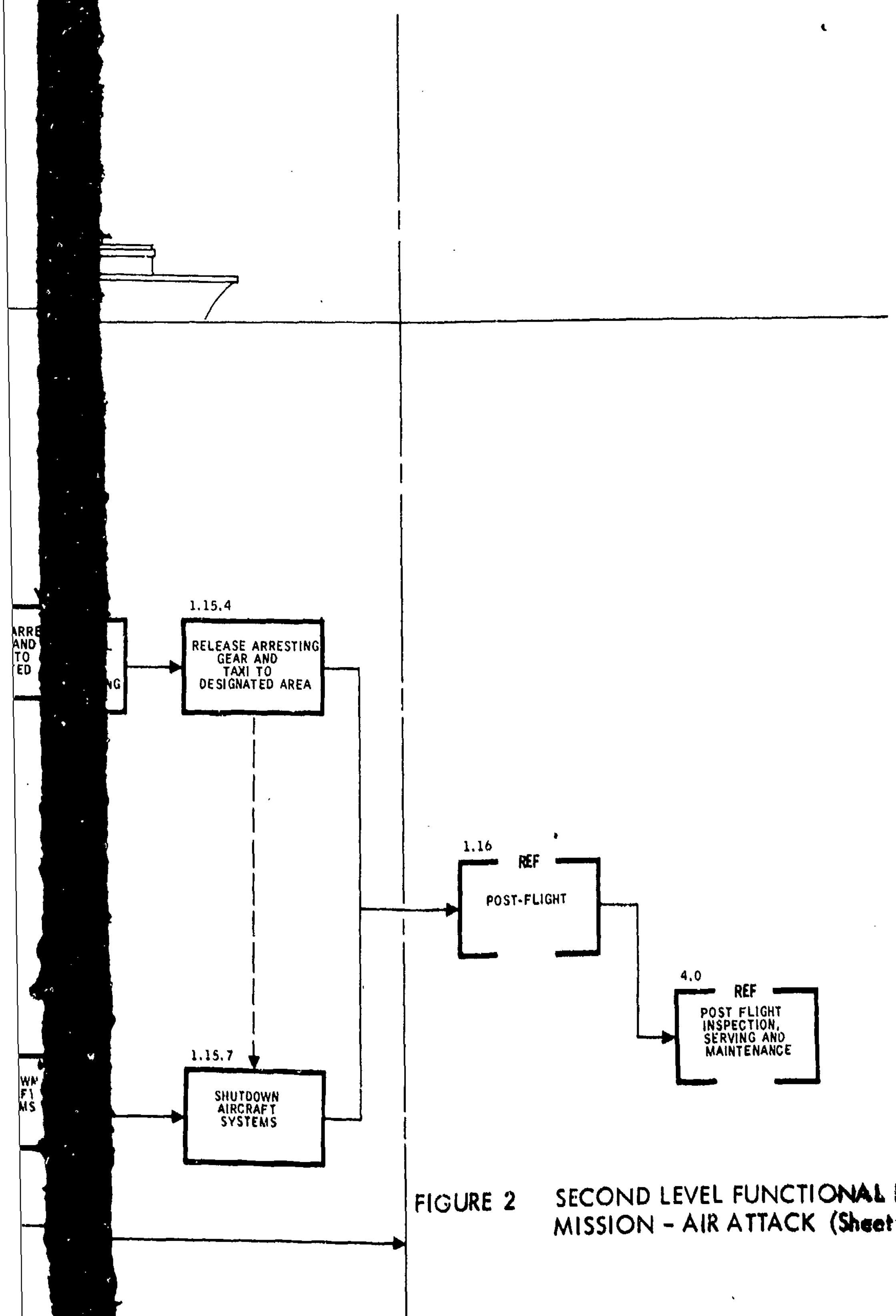


FIGURE 2 SECOND LEVEL FUNCTIONAL FLOW MISSION OPERATIONS - INTERDICTION MISSION - AIR ATTACK (Sheet 2 of 2)

CCA	-	Carrier Controlled Approach
CIC	-	Combat Information Center
ETA	-	Estimated Time of Arrival
EW	-	Early Warning
FLIR	-	Forward Looking Infrared System
FLR	-	Forward Looking Radar System
IFF	-	Identification Friend or Foe System
IP	-	Initial Point
RHAW	-	Radar Homing and Warning System
S.O.	-	Systems Operator
TISEO	-	Target Identification System, Electro-Optical
TOT	-	Time Over Target
VDS	-	Vertical Display System
WDS	-	Weapon Delivery System

1.4 MISSION SCENARIO NO. 1

The mission scenario developed in this example is representative of possible Naval operations in any theater of operations. It is assumed that an amphibious assault landing has been scheduled within 24 to 48 hours of launch, depending upon weather and sea conditions. An attack carrier task force has been committed to support the assault. Pre-assault interdiction raids are to be carried out against the enemy's airbases, defenses, logistics and transportation routes in the assault area to isolate the beachhead. This mission is a pre-dawn attack where the time over target (TOT) will be prior to first light as calculated from nautical twilight. Weather at sea during launch and recovery is forecast to be marginal due to fog and low clouds. Weather on the coast is forecast to be "socked-in" with zero visibility. Visibility enroute to the target is forecast to be 1 to 2 miles, gradually improving inland, with visibility in the target area varying from 2 to 3 miles. The terrain between the coast and the target consists of flat terrain, low rolling hills and several small mountains with elevations to 4500 feet. The route has been selected so that a low-attitude approach can be made using terrain following and terrain avoidance modes up to the initial point (IP). The target area is expected to be defended by surface-to-air missiles and anti-aircraft artillery. To take advantage of the element of surprise, a high-speed, low-altitude approach has been chosen. This mission profile provides a high probability of mission success while minimizing losses due to enemy ground-to-air defensive weapons. Escape from the target area will be at a minimum altitude using terrain avoidance and terrain following modes. Threat detection equipment will be monitored throughout the mission. ECM gear and air-to-air missiles will be carried and employed as required for protection.

It is assumed that the Flight Director System (FDS) will incorporate data from a satellite navigation system and be capable of accepting digital flight plan data for automatic naviation and/or programmed flight control at the operator's option. In either case, flight plan data will normally be available for display, either automatically or upon query by the aircrew.

For this mission, it is assumed that although programmed automatic flight plan, profile and weapon delivery information has been prepared and stored in the FDS, the execution of this mission phase will be controlled by the aircrew.

This assumption is based on the possibility that the navigation and target charts may be in error, and the target data is out of date due to previous restrictions relative to overflight reconnaissance.

The operational sensors utilized during Mission No. 1 are:

a. Forward Looking Radar
b. Forward Looking Infrared
c. RHAW
d. ASIR
e. IFF/SIF
f. TISEO
g. Ground Mapping Radar

The operational weapons that may be employed on Mission No. 1 are:

a. Bombs (conventional - high explosive)
b. Guided Missiles - Air-to-Air (target seeking)

In the remaining portion of this scenario the first-level functions are further detailed to provide a baseline for the development of the second-level functional flow diagrams. The first-level functions depicted in Figure 1 are now used to establish the major mission phases at the second level.

Sheets 1 and 2 of Figure 2 present the second-level functions and sequential flow of the mission operations described in this scenario.

In the following paragraphs, specific crew tasks are described in relation to the mission progression and identify those operations which must be accomplished during a particular phase prior to entering the subsequent phase.

FUNCTION 1.1 - PREFLIGHT AIRCRAFT

The pilot and S.O. conduct a system check (go/no-go) following engine run-up and aircraft checkout. This function is not broken out at the second level functions, as there are no new or additional information requirements generated by this function which would be displayed on the VDS.

FUNCTION 1.2 - LAUNCH AIRCRAFT

The mission aircraft is launched from the attack carrier in darkness in near zero-zero conditions. Strike is scheduled to occur in darkness just prior to first light before dawn. After the pilot and the systems operator have performed all prelaunch checks and upon the signal of the deck officer, the aircraft is taxied to the catapult. The catapult is attached and after final cockpit checks, including the S.O.'s final update of the inertial guidance system, the pilot signals ready for takeoff. After catapult launch and release the pilot maintains the proper attitude, safe altitude and retracts gear and flaps. He then permits the aircraft to accelerate to best climb speed.

FUNCTION 1.3 - CLIMB/DEPARTURE

This mission phase encompasses the climb immediately after launch and the establishment of departure heading, altitude, airspeed and systems configuration.

As soon as the aircraft has become safely airborne with gear and flaps retracted, a climb is initiated. Pitch attitudes are varied to maintain a safe climb speed in accordance with the predetermined climb schedule until reaching a departure altitude dictated by enemy defensive capability. Here it is assumed the cruise out will be accomplished at 1000 feet absolute altitude.

FUNCTION 1.4 - CRUISE-OUT

This mission phase encompasses the enroute cruise from the departure point to the penetration point where Early Warning (EW) contact may be expected.

a. Upon leaving the departure point, the pilot establishes the pre-planned cruise airspeed for the low-level flight altitude selected, here assumed to be 1000 feet. The flight plan heading and altitude is maintained to the penetration point.

b. The system operator performs an in-flight check of all systems, verifies their operational status and places the FLR system in standby mode to prevent early detection. The ASIR and RHAW (passive) systems will be on and monitored by the S.O.

c. The pilot verifies the S.O.'s aircraft and avionic systems checks to ensure that the aircraft can perform its primary mission.

d. Prior to the ETA at the penetration control point, the system operator verifies the aircraft position from data supplied by the Flight Director System (FDS) and advises the pilot when to start descent to the penetration altitude.

e. The pilot "lets down" on instruments to the pre-planned penetration altitude, here assumed to be 100 feet absolute.

FUNCTION 1.5 - PENETRATE

This mission phase encompasses the penetration of the enemy EW system coverage and the coastal penetration over hostile territory where pre-attack activities are commenced.

a. While letting down to the EW penetration point, the pilot establishes the penetration airspeed (1.2 mach). He trims the aircraft to maintain level flight upon reaching penetration altitude.

b. The crew selects pre-planned radar modes which will be used in penetration and attack and places the radar equipment on standby until within approximately 20 nm of the coastal penetration point. Upon reaching this position, the radar is enabled and the pilot and S.O. adjust their VDS's for the appropriate radar imagery.

c. When the coastline appears on the pilot's and system operator's displays, the pilot establishes the penetration heading and altitude. The system operator verifies the position of the aircraft at the coastal penetration point, updating the FDS if required.

d. Since the coastal plain over which penetration is to be made consists of low rolling hills, terrain following at the pre-planned altitude, here assumed to be 250 feet, is established.

FUNCTION 1.6 - PRE-ATTACK (AIR/GROUND WEAPON DELIVERY)

This mission phase encompasses the approach to the initial point (IP), the acquisition of the IP by the on-board sensor display(s), and the establishment of the heading and flight conditions and equipment configurations to successfully complete the weapon delivery.

a. On the approach to the IP the pilot maintains the pre-planned clearance over the terrain, holding the flight plan heading and airspeed.

b. The system operator monitors the mission progress. Based on the flight plan estimated time of arrival (ETA) for the IP, he anticipates its appearance and configures the FLR for acquisition of the IP. The IP, assumed to be an island in a large lake, has been selected for its unique radar features.

c. After configuring the FLR equipment for optimum ground feature presentation, he monitors the FLR display in order to acquire and identify the IP. When he detects and identifies the IP as briefed, he refers to the flight plan coordinates of the IP, comparing the NAV system coordinates with the given coordinates. As the aircraft passes close to or over the IP, the system operator updates the inertial navigation system, or verifies the accuracy of the NAV system coordinates as being within an acceptable tolerance limit. Just prior to passing over the IP, the pilot is provided with the new required heading for the target. If the IP was not made good (passing to the side), the flight plan heading will be adjusted to compensate for the deviation in track, and the new heading (adjusted) will be provided to the pilot. Updating of the NAV system may also be accomplished enroute by reference to the Satellite Navigation System data.

d. Using the heading data provided, the pilot establishes the new heading and attitude for initiating the target approach. In order to minimize the chance for acquisition by ground defensive EW systems, the pre-planned minimum safe altitude is maintained using terrain following and terrain avoidance modes. Smoke abatement procedures are initiated by the pilot to reduce the aircraft's visible signature prior to entering the target area.

e. While the pilot is establishing the new heading, the system operator configures the WDS for the pre-planned attack. Here it is assumed that conventional weapons such as the MK-82 (high drag) will be used against the target. Bombing approach, release altitudes, airspeeds and weapon ballistic data are determined and the preplanned data are verified. The pilot confirms the WDS selections and preset data, enabling the system when all delivery parameters have been verified.

f. After configuring and verifying the WDS selections, the system operator configures the FLR and FLIR sensors for acquiring the target and delivering the weapon. Two sensors, working in conformation with each other, have been selected as the optimum target display. The FLR was selected in order to be able to acquire the target at sufficient range to insure the proper approach course. The FLIR was selected in order to provide additional detail (resolution) in the target area so that a specific aiming point can be identified. An added benefit of the FLIR is that it is passive and may be used for final aiming point refinement in the event the enemy should employ ECM against the FLR.

g. After configuring the FLR/FLIR equipment and verifying their operational status, the system operator searches for the target area as it may be observed on the attack approach. It is not expected that the target will show until increase in altitude (pop-up) is made at approximately 8 nm from the target. The time to pull-up has been computed from the IP as a control point and is contained in the pre-planned mission data.

FUNCTION 1.7 - BOMB ATTACK

This mission phase encompasses the final run into the target area, the detection, identification and selection of the target aiming point, weapon release and aircraft withdrawal maneuver after "bombs away." Using a low level attack with a pop-up maneuver executed approximately 45 seconds prior to weapon release, hostile reaction time is minimized, resulting in an increased probability of mission success and aircraft survivability.

a. In conformance with the flight plan, a "pop-up" is made to the predetermined altitude at the indicated time. The pilot during the pop-up reduces airspeed to approximately 0.92 Mach. At level-off altitude,

airspeed is stabilized for the run to the target. With the increase in altitude, the target is to be illuminated by radar. The system operator detects and identifies the pre-planned target, providing target designation information to the pilot.

b. The pilot, using the target designator information locates the target and initiates target tracking, entering the requisite 10 degree dive for the MK-82 weapon. The system operator confirms that the aiming point has been located. The FLR data display provides target ranging information, while the FLIR data display provides additional target detail for accurate aiming point positioning.

c. After confirming that the pilot has the aiming point precisely located, the system operator monitors the RHAW and ASIR for possible air intercept by hostile aircraft and/or surface-to-air missile launch.

d. As the aircraft closes on the target, the pilot continues target tracking, initiates the final aircraft alignment with the target, and releases the weapons. The system operator confirms weapon release by reference to the WDS data. After "bombs away" the pilot takes the pre-planned evasive maneuver to clear the target area. The system operator configures the FLR for terrain following/terrain avoidance mode.

FUNCTION 1.8 - POST ATTACK

This mission phase encompasses clearing the target area, including target damage assessment if visibility permits, and communication of the strike report if required in the mission plan.

It is assumed that during the evasive maneuver after weapon release, the S.O. will verify weapon detonation on target, and will make whatever target damage assessment is possible. These data are then prepared for strike report transmission. As the pilot rolls out on the escape heading provided by the flight plan, the WDS is placed in SAFE configuration by the system operator, and verified by the pilot.

FUNCTION 1.9 - ESCAPE

This mission phase encompasses the low altitude escape from the target area. It includes establishment of the escape mission heading, altitude and airspeed as pre-planned. Monitoring the RHAW equipment for detection of enemy counteraction is essential during this phase.

a. While clearing the target area, it is assumed that the pilot accelerates to 1.2 Mach. After rolling out on the required heading, descent to the pre-planned escape altitude is accomplished. A minimum safe altitude above the terrain is maintained.

b. The system operator, using the target area as a departure point, determines and verifies the escape course/heading and provides the pilot with heading information. Both the S.O. and the pilot monitor the RHAW equipment for hostile enemy aircraft and/or surface to air missile activity. It is assumed that the system operator detects radiation from possible enemy aircraft in the forward sector and notifies the pilot of the potential threat. Upon detecting a signal indicating air-to-air scan and lock-on, jamming of the threat is immediately attempted. If the jamming is successful, the aircraft continues its pre-planned escape. If, however, the jamming is not successful, the pilot must make a decision whether to attack the potential threat or accelerate to maximum speed and attempt evasive maneuvers. Since it is probable that the threat is an enemy high altitude interceptor equipped with moving target "look down" radar and "shoot down" missiles, the pilot decides that he must attempt to destroy the threat with counterair missiles. Assuming the potential threat is indeed an enemy, and assuming that the counterair action is successful, the aircraft resumes its pre-planned escape. (The air-to-air attack functions 1.10 - 1.12 follow this function.)

c. After completing a successful air attack, the pilot re-establishes the heading for the coast-out point, making a rapid descent to continue a low-level escape. Though it would be advantageous, from a fuel conservation standpoint, to exit at high altitude, hostile surface-to-air missile defenses dictate a low-level escape to the coast. After descent, terrain following and avoidance tactics are employed using the FLR as the primary piloting aid. The system operator continues to monitor the RHAW and ASIR for indications of hostile activity, and assists the pilot in low altitude navigation.

d. As the mission aircraft approaches the coast, the FLR provides a display of the coastline and a departure fix is established by the system operator. As the coast is crossed, the system operator provides the pilot with a new heading, safe altitude and ETA for the marshaling point. The pilot establishes the new heading and altitude, and reduces power to optimum cruise airspeed.

FUNCTION 1.10 - PRE-ATTACK (AIR-TO-AIR)

This mission phase encompasses the preparation for an air-to-air attack using long range missiles.

a. In preparation for the attack against the possible enemy aircraft, the pilot configures the radar system for air search and initiates a pull-up into a maximum rate climb using appropriate power settings. Concurrent with the pilot's action, the system operator configures the TISEO system and checks his IFF equipment configuration status. Subsequently, the system operator configures the WDS for a missile attack.

b. Upon completion of these tasks, the pilot confirms the WDS weapon selection and arms the system. The system operator and pilot continue to monitor the warning display for radiations indicating bearing to the target and type of hostile action/intent. As the mission aircraft climbs, the search for the possible hostile aircraft continues until radar detection is accomplished.

FUNCTION 1.11 - MISSILE ATTACK

This mission phase encompasses the detection, identification, interception maneuver and missile launch at the hostile aircraft.

a. The search for the possible hostile aircraft continues until detection is made by the intercept radar. Upon detection, the pilot maneuvers the aircraft for position advantage so that a missile may be launched. The attack cannot be made until the aircraft has been identified as friendly or hostile. Since friendly aircraft are known to be flying cover for this sortie and other sorties in the assault area, positive identification is required. The system operator interrogates the possible hostile aircraft with IFF/SIF and attempts visual identification with TISEO. The presence of scattered clouds prevents TISEO acquisition. The results of IFF/SIF interrogation are negative.

b. Since no response is received from the unknown aircraft, it is presumed as hostile, the decision to launch a missile is made by the pilot. When the mission aircraft has maneuvered into firing position as determined by the intercept radar, the missile is launched. The pilot elects to continue closing after the launch of the first missile in the event the second missile is needed.

FUNCTION 1.12 - POST ATTACK (AIR-TO-AIR)

This mission phase encompasses the determination of the success of the attack (hostile aircraft disablement or destruction), the search for additional hostile aircraft and the continuation of the mission back to base.

a. Several seconds after launch of the missile, the radar on the hostile aircraft terminates transmission and the single radar blip is replaced by several small returns on the intercept radar display. Immediately, the pilot terminates the intercept maneuver, turning to the heading previously being flown and descending to terrain clearance altitude.

b. At this time, both the pilot and system operator check and verify the status of all aircraft systems. The system operator returns the WDS to SAFE, and his action is verified by the pilot. A search for other aircraft in the area is continued as the mission aircraft proceeds to the coast-out point.

c. While continuing the search for other aircraft, a contact is made; however, on interrogation, it is determined to be friendly and from the approximate range and distance it is believed to be part of the friendly air cover being provided the attack force.

FUNCTION 1.13 - CRUISE-BACK

This mission phase encompasses the enroute cruise from the EW line to the marshaling point.

a. At a predetermined time, the S.O. establishes contact with the Combat Information Center (CIC), is interrogated and identified, and receives bearing, range and altitude information to the marshaling point.

b. After coast-out, the pilot establishes a specified altitude cruise configuration to the marshaling point which is beyond the enemy EW line.

c. The system operator continues to monitor the RHAW and ASIR equipment for possible enemy interception. At the option of the CIC, and depending upon fuel state, traffic, and other variables, the CIC may clear the aircraft for landing or have it hold at the marshaling point.

FUNCTION 1.14 - CARRIER RENDEZVOUS

This mission phase encompasses the arrival at the marshaling point, the holding pattern or immediate letdown to landing pattern altitude, and initiation of the Carrier Controlled Approach (CCA) system. Weather in the area is such that an instrument approach and landing is required.

a. After coast-out, a cruise configuration has been maintained. Communications contact with the CIC was made and the aircraft identified. At the marshaling point, all returning aircraft may be held in patterns at specified altitudes until cleared for carrier landing. Upon reaching the marshaling point, the CIC provides the pilot with the holding pattern, airspeed and altitude information, or turns the pilot over to CCA for approach. The pilot may verify position by reference to the FLR display which has picked up the task force.

b. Upon being cleared by CCA for carrier approach, the pilot configures the aircraft for landing. The S.O. verifies the configuration is correct for landing. The pilot establishes the specified penetration airspeed, heading, and rate of descent, following the instructions of the CCA controller.

FUNCTION 1.15 - RECOVER AIRCRAFT

The mission phase covers the CCA to carrier landing from departure point of the marshaling area to taxi and system shutdown onboard the carrier under instrument flight conditions.

a. After configuring the aircraft for landing and establishing the approach airspeed, heading, and rate of descent, the pilot and S.O. continue to monitor the VDS and to correct flight path deviations. The S.O.'s primary

responsibility during this phase is to assist the pilot by monitoring the various aircraft subsystems and verifying that the airspeed, heading, angle of attack, and rate of descent is in accordance with displayed commands.

b. The pilot makes corrections to flight path as required, and continues his approach until he receives a "wave-off" command or until his tail hook engages the cable. After successful arrestment, he taxies to the designated point on the deck for system shutdown immediately upon cable release. The S.O. shu' down all unnecessary subsystems while the aircraft is being taxied, and assists the pilot in securing the aircraft after engines are shut down.

FUNCTION 1.16 - POST FLIGHT

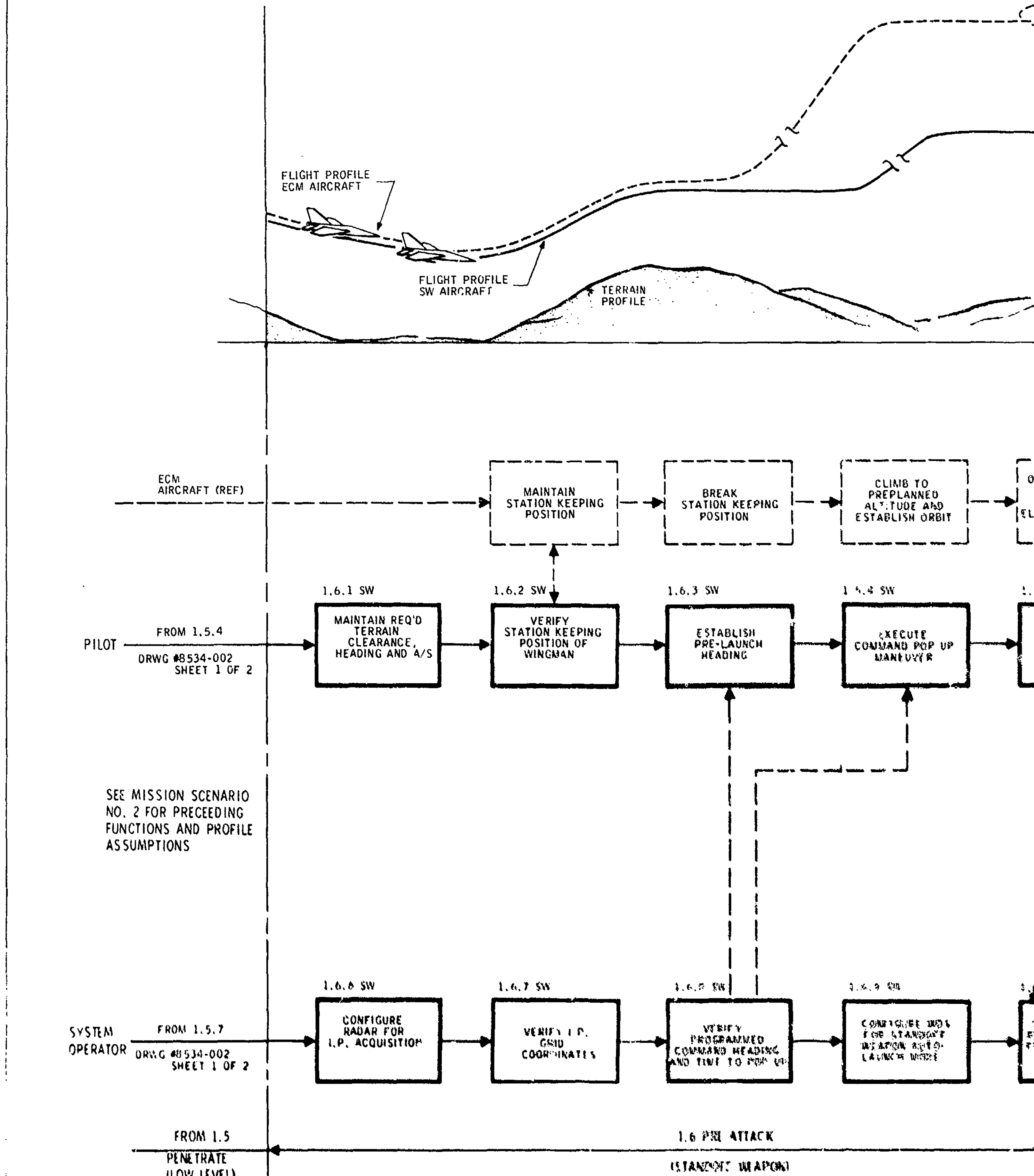
This function is not broken out at the second level, as there are no additional information requirements generated by this function which would be displayed on the VDS.

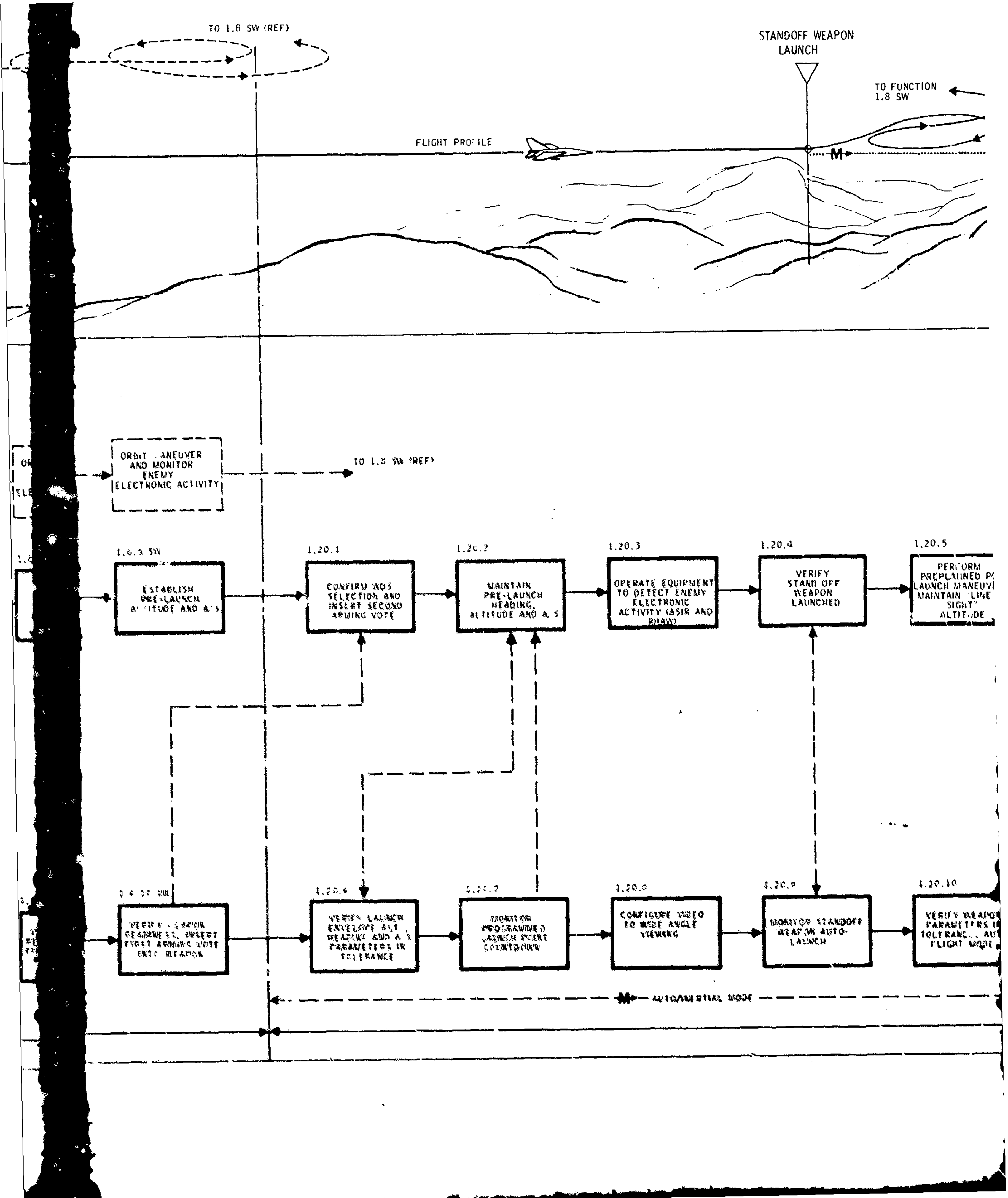
1.5 MISSION NO. 2 - EXECUTION DESCRIPTION

Figure 3 depicts the second level functions, the mission profile and the mission plan for the Standoff Weapon Attack/Interdiction Mission (first-level function 1.20). The flight profile associated with each mission phase is shown above the applicable functions. The vertical phantom lines indicate the scope of the individual first level mission phases as referenced along the bottom of the drawing.

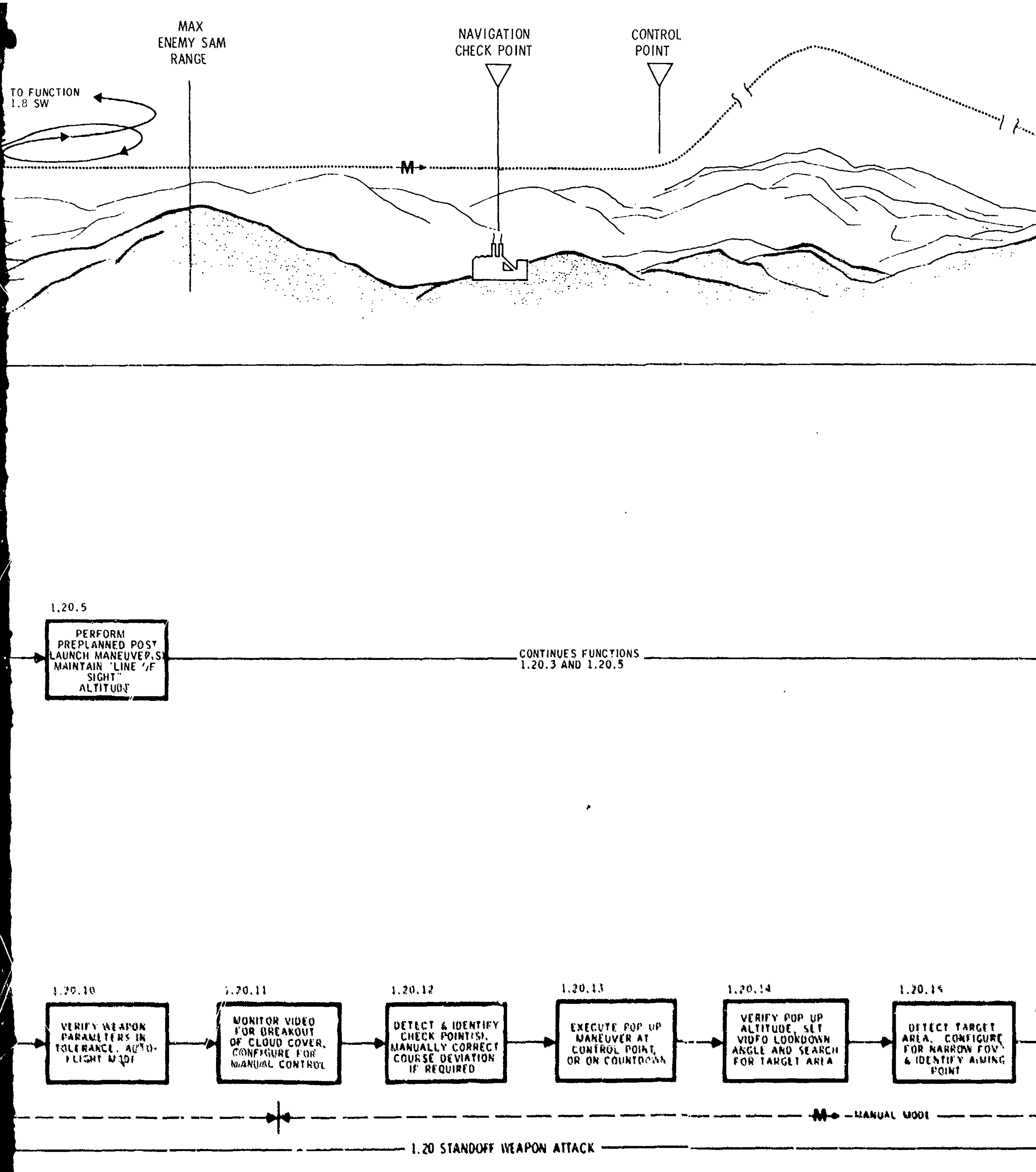
The format of Figure 3 is slightly different from Figures 1 and 2 in two aspects. First, a two element flight consisting of the attack aircraft delivering a standoff weapon, and an ECM aircraft (ECM a/c) which provides additional electronic countermeasure and defensive capability, was postulated to exercise stationkeeping requirements and formation flying interactions. The ECM aircraft functions are shown as dotted blocks above the concurrent time/sequence functions performed by the Standoff Weapon aircraft (SW a/c) pilot. Secondly, reference functions were introduced into the pilot and system operator flows to minimize repeating the mission functions which are redundant with those depicted in the Second Level Functional Flow Diagrams for Mission No. 1 - (Bomb Attack). Examples of these referenced functions are: 1.13 Cruise Back and 1.15 Recover Aircraft. Again, to avoid redundancy it was assumed that the functions associated with Launch Aircraft, Climb/Departure, Cruise Out and Penetrate were identical to those developed for Mission No. 1, with the exception that this mission utilizes a preprogrammed flight plan with the Standoff Weapon aircraft flying lead and the ECM aircraft as the wingman. The "join-up" and "stationkeeping" functions, which would have occurred prior to the Penetration Phase are developed in the Post Attack and Escape Phases, where these functions are repeated.

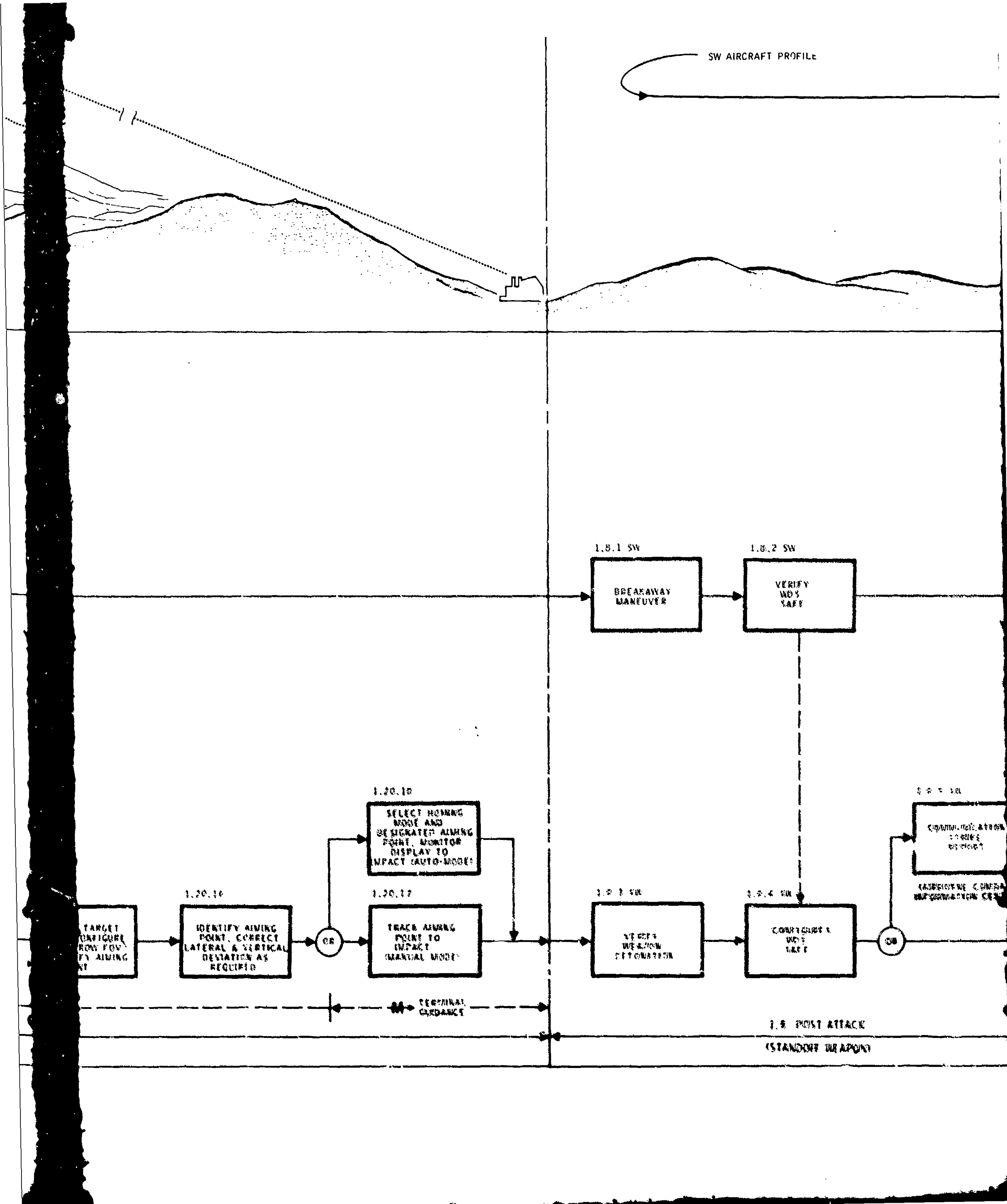
Section 1.5.1 contains a brief outline of the 1985 Standoff Weapon parameters. This weapon is entirely hypothetical and includes several control options which utilize the display capabilities at the System Operator's crew station. As the control options for the Standoff Weapon were developed, the similarity of the information and control/display requirements for this weapon system and a remotely piloted aircraft (RPA) were noted. By substituting variable thrust for the constant thrust postulated and coordinated turn (Roll) information in place of


FLIGHT PROFILE
ECM AIRCRAFT
FLIGHT PROFILE
SW AIRCRAFT
TERRAIN
PROFILE
ECM
AIRCRAFT (REF)
MAINTAIN STATION KEEPING POSITION
BREAK STATION KEEPING POSITION
CLIMB TO PREPLANNED ALTITUDE AND ESTABLISH ORBIT
PILOT
FROM 1.5.4
DRWG #8534-002
SHEET 1 OF 2
1.6.1 SW
MAINTAIN REQ'D TERRAIN CLEARANCE, HEADING AND A/S
1.6.2 SW
VERIFY STATION KEEPING POSITION OF WINGMAN
1.6.3 SW
ESTABLISH PRE-LAUNCH HEADING
1.6.4 SW
EXECUTE COMMAND POP UP MANEUVER
SEE MISSION SCENARIO NO. 2 FOR PRECEEDING FUNCTIONS AND PROFILE ASSUMPTIONS
SYSTEM
OPERATOR
FROM 1.5.7
DRWG #8534-002
SHEET 1 OF 2
1.6.6 SW
CONFIGURE RADAR FOR I.P. ACQUISITION
1.6.7 SW
VERIFY I.P. GRID COORDINATES
VERIFY PROGRAMMED COMMAND HEADING AND TIME TO POP UP
FROM 1.5
PENETRATE
(LOW LEVEL)
1.6 PRE ATTACK
(STANDOFF WEAPON)

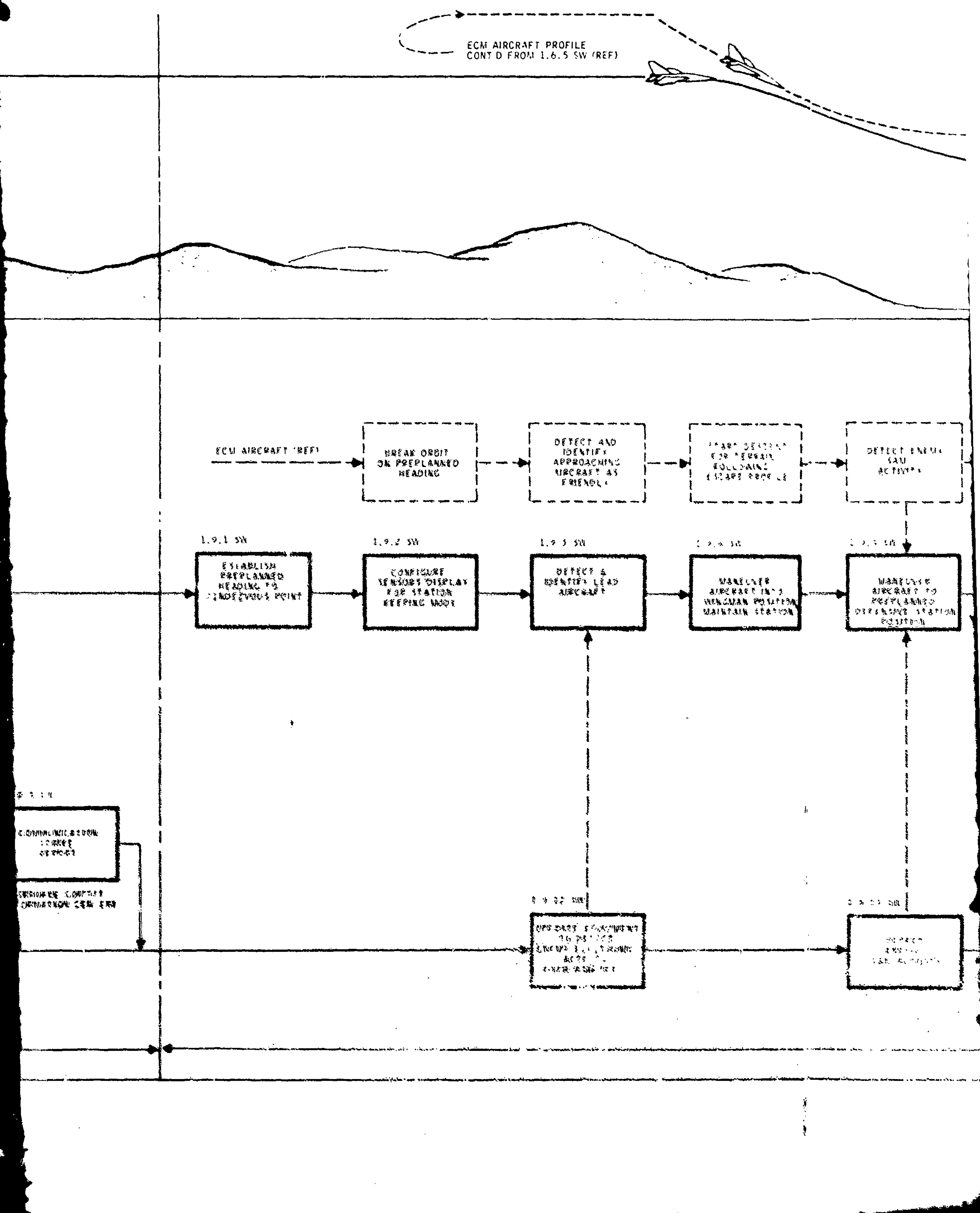


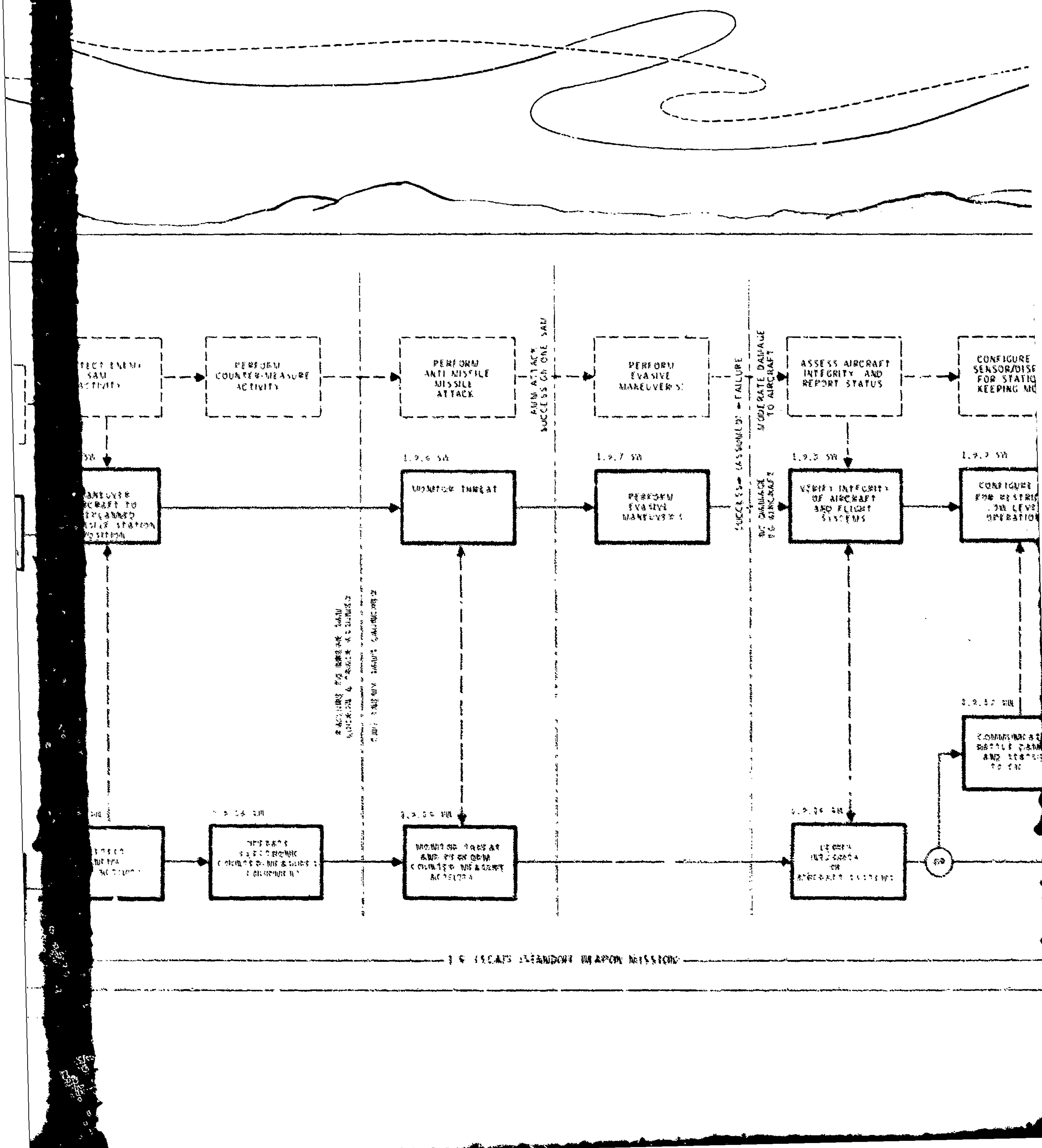
TO 1.8 SW (REF)
STANDOFF WEAPON LAUNCH
TO FUNCTION 1.8 SW
FLIGHT PROFILE
M
ORBIT MANEUVER AND MONITOR ENEMY ELECTRONIC ACTIVITY
TO 1.8 SW (REF)
1.6.9 SW
ESTABLISH PRE-LAUNCH ALTITUDE AND A/S
1.20.1
CONFIRM WOS SELECTION AND INSERT SECOND ARMING VOTE
1.20.2
MAINTAIN PRE-LAUNCH HEADING, ALTITUDE AND A/S
1.20.3
OPERATE EQUIPMENT TO DETECT ENEMY ELECTRONIC ACTIVITY (ASIR AND RHAW)
1.20.4
VERIFY STAND OFF WEAPON LAUNCHED
1.20.5
PERFORM PREPLANNED LAUNCH MANEUVER MAINTAIN "LINE SIGHT" ALTITUDE
1.20.8
CONFIGURE VIDEO TO WIDE ANGLE VIEWING
1.20.10
AUTO/INERTIAL MODE


MAX
ENEMY SAM
RANGE
NAVIGATION
CHECK POINT
CONTROL
POINT
TO FUNCTION
1.8 SW
M
1.20.5
PERFORM PREPLANNED POST LAUNCH MANEUVER(S) MAINTAIN "LINE OF SIGHT" ALTITUDE
CONTINUES FUNCTIONS
1.20.3 AND 1.20.5
1.20.10
VERIFY WEAPON PARAMETERS IN TOLERANCE, AUTO-FLIGHT MODE
1.20.11
MONITOR VIDEO FOR BREAKOUT OF CLOUD COVER, CONFIGURE FOR MANUAL CONTROL
1.20.12
DETECT & IDENTIFY CHECK POINT(S), MANUALLY CORRECT COURSE DEVIATION IF REQUIRED
1.20.13
EXECUTE POP UP MANEUVER AT CONTROL POINT, OR ON COUNTDOWN
1.20.14
VERIFY POP UP ALTITUDE, SET VIDEO LOOKDOWN ANGLE AND SEARCH FOR TARGET AREA
1.20.15
DETECT TARGET AREA, CONFIGURE FOR NARROW FOV & IDENTIFY AIMING POINT
M
MANUAL MODE
1.20 STANDOFF WEAPON ATTACK

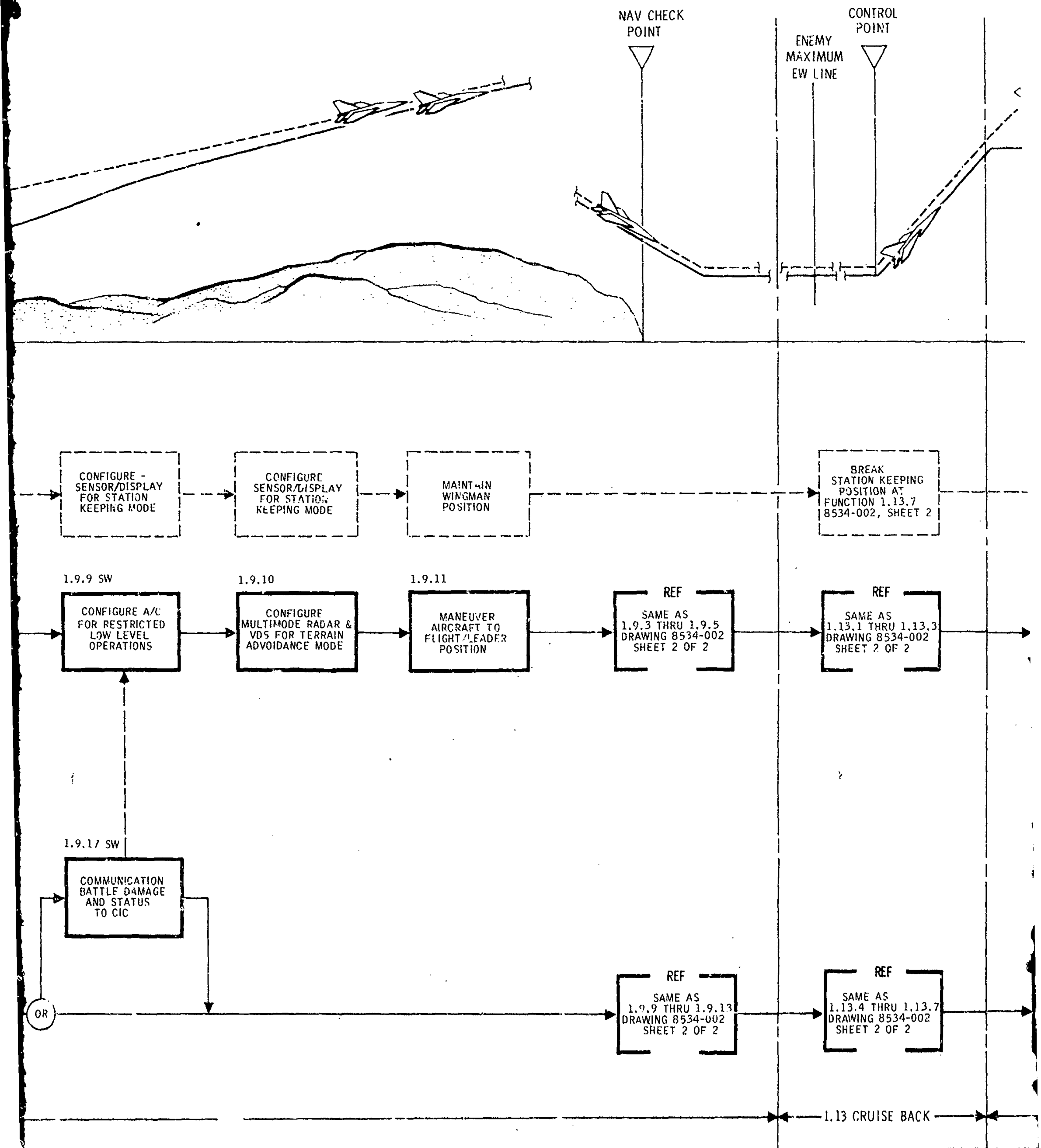


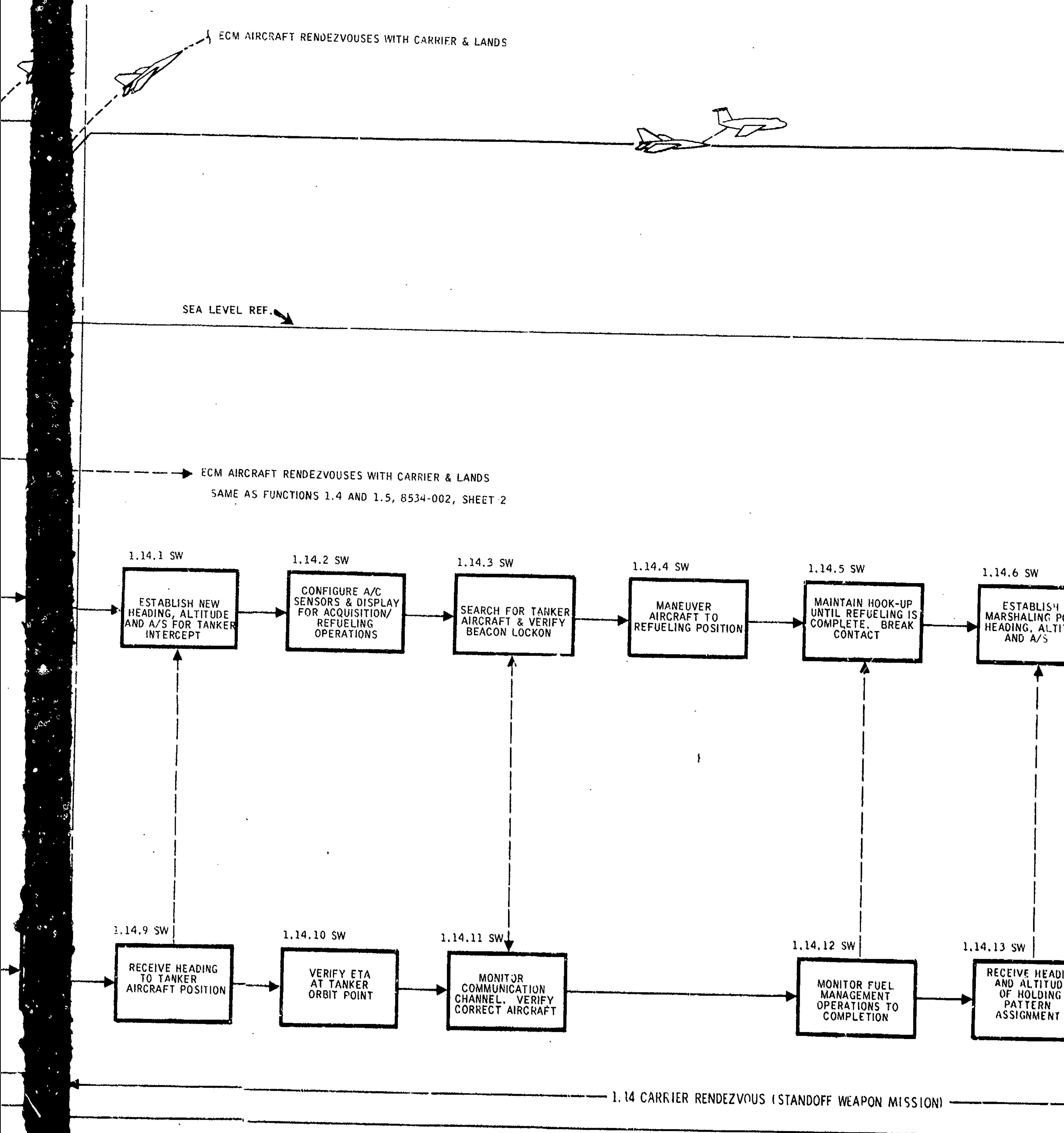
SW AIRCRAFT PROFILE
1.8.1 SW
BREAKAWAY MANEUVER
1.8.2 SW
VERIFY WDS SAFE
1.20.18
SELECT HOMING MODE AND DESIGNATED AIMING POINT, MONITOR DISPLAY TO IMPACT (AUTO-MODE)
TARGET
1.20.16
IDENTIFY AIMING POINT, CORRECT LATERAL & VERTICAL DEVIATION AS REQUIRED
OR
1.20.17
TRACK AIMING POINT TO IMPACT (MANUAL MODE)
TERMINAL GUIDANCE
1.8 POST ATTACK
(STANDOFF WEAPON)

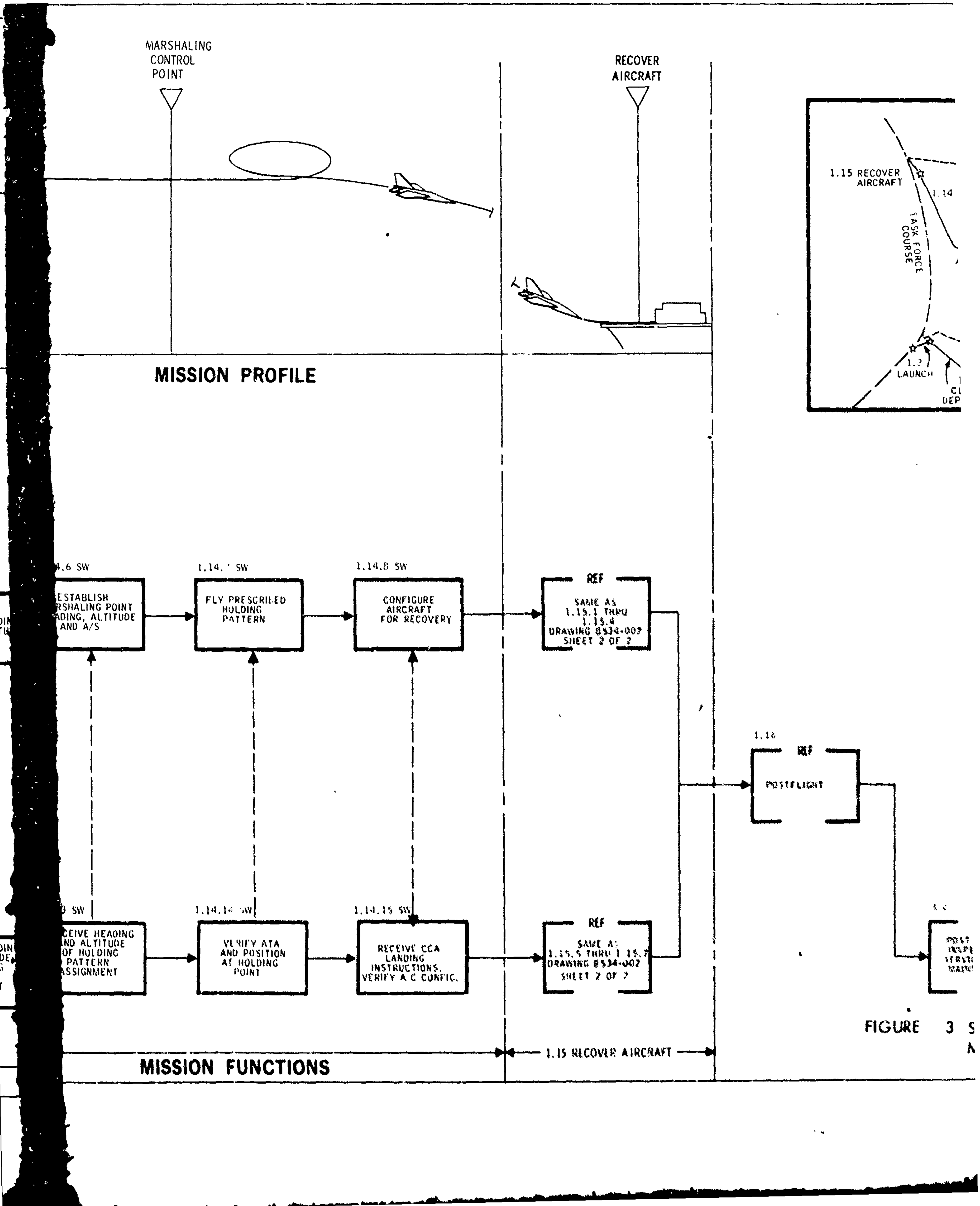

ECM AIRCRAFT PROFILE
CONT'D FROM 1.6.5 SW (REF)
ECM AIRCRAFT (REF)
BREAK ORBIT ON PREPLANNED HEADING
DETECT AND IDENTIFY APPROACHING AIRCRAFT AS FRIENDLY
1.9.1 SW
ESTABLISH PREPLANNED HEADING TO RENDEZVOUS POINT
1.9.2 SW
CONFIGURE SENSORS DISPLAY FOR STATION KEEPING MODE
1.9.3 SW
DETECT & IDENTIFY LEAD AIRCRAFT
MANEUVER AIRCRAFT INTO WINGMAN POSITION MAINTAIN STATION

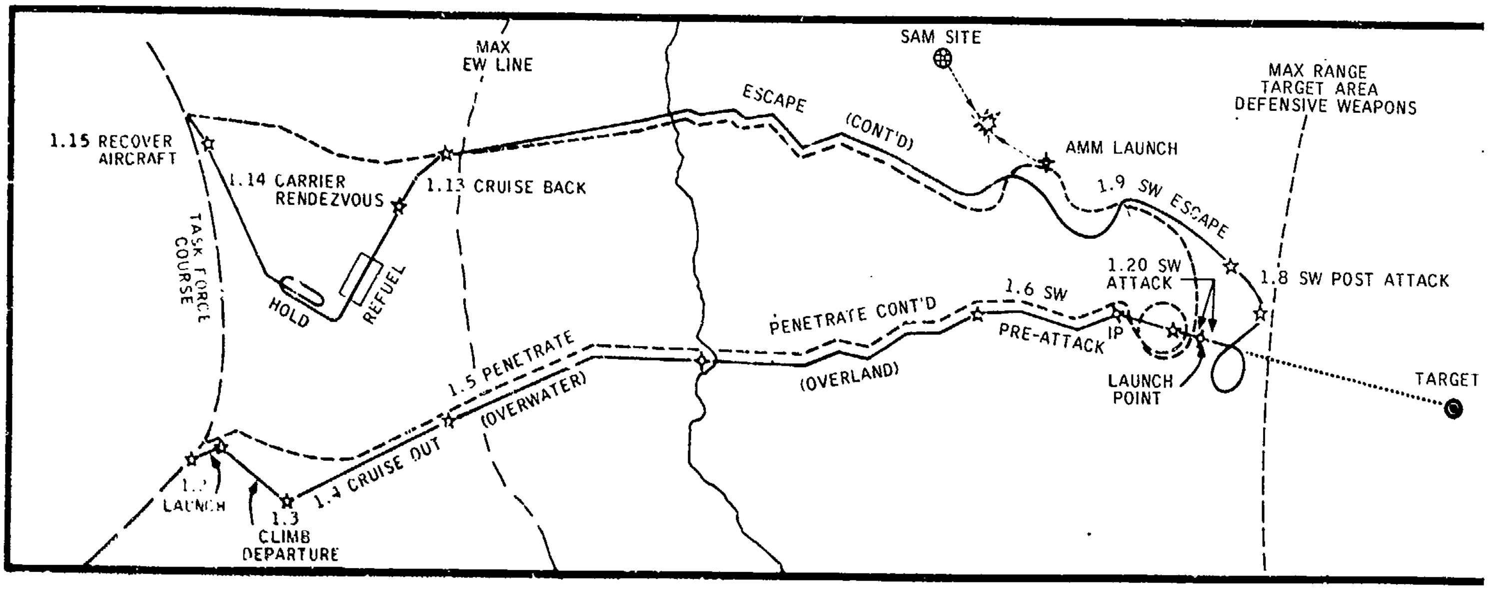


PERFORM COUNTER-MEASURE ACTIVITY
PERFORM ANTI MISSILE MISSILE ATTACK
AMM ATTACK SUCCESS ON ONE SAM
PERFORM EVASIVE MANEUVERS
SUCCESS — (ASSUMED) — FAILURE
MODERATE DAMAGE TO AIRCRAFT
ASSESS AIRCRAFT INTEGRITY AND REPORT STATUS
1.9.6 SN
MONITOR THREAT
1.9.7 SN
PERFORM EVASIVE MANEUVERS
NO DAMAGE TO AIRCRAFT
VERIFY INTEGRITY OF AIRCRAFT AND FLIGHT SYSTEMS


NAV CHECK POINT
ENEMY MAXIMUM EW LINE
CONTROL POINT
CONFIGURE - SENSOR/DISPLAY FOR STATION KEEPING MODE
CONFIGURE SENSOR/DISPLAY FOR STATION KEEPING MODE
MAINTAIN WINGMAN POSITION
BREAK STATION KEEPING POSITION AT FUNCTION 1.13.7 8534-002, SHEET 2
1.9.9 SW
CONFIGURE A/C FOR RESTRICTED LOW LEVEL OPERATIONS
1.9.10
CONFIGURE MULTIMODE RADAR & VDS FOR TERRAIN ADVOIDANCE MODE
1.9.11
MANEUVER AIRCRAFT TO FLIGHT/LEADER POSITION
REF
SAME AS 1.9.3 THRU 1.9.5 DRAWING 8534-002 SHEET 2 OF 2
REF
SAME AS 1.13.1 THRU 1.13.3 DRAWING 8534-002 SHEET 2 OF 2
1.9.17 SW
COMMUNICATION BATTLE DAMAGE AND STATUS TO CIC
OR
REF
SAME AS 1.9.9 THRU 1.9.13 DRAWING 8534-002 SHEET 2 OF 2
REF
SAME AS 1.13.4 THRU 1.13.7 DRAWING 8534-002 SHEET 2 OF 2
1.13 CRUISE BACK


ECM AIRCRAFT RENDEZVOUSES WITH CARRIER & LANDS
SEA LEVEL REF.
ECM AIRCRAFT RENDEZVOUSES WITH CARRIER & LANDS
SAME AS FUNCTIONS 1.4 AND 1.5, 8534-002, SHEET 2
1.14.1 SW
ESTABLISH NEW HEADING, ALTITUDE AND A/S FOR TANKER INTERCEPT
1.14.2 SW
CONFIGURE A/C SENSORS & DISPLAY FOR ACQUISITION/ REFUELING OPERATIONS
1.14.3 SW
SEARCH FOR TANKER AIRCRAFT & VERIFY BEACON LOCKON
1.14.4 SW
MANEUVER AIRCRAFT TO REFUELING POSITION
1.14.5 SW
MAINTAIN HOOK-UP UNTIL REFUELING IS COMPLETE. BREAK CONTACT
1.14.6 SW
ESTABLISH MARSHALING PO HEADING, ALTI AND A/S
1.14.9 SW
RECEIVE HEADING TO TANKER AIRCRAFT POSITION
1.14.10 SW
VERIFY ETA AT TANKER ORBIT POINT
1.14.11 SW
MONITOR COMMUNICATION CHANNEL. VERIFY CORRECT AIRCRAFT
1.14.12 SW
MONITOR FUEL MANAGEMENT OPERATIONS TO COMPLETION
1.14.13 SW
RECEIVE HEADI AND ALTITUD OF HOLDING PATTERN ASSIGNMENT
1.14 CARRIER RENDEZVOUS (STANDOFF WEAPON MISSION)

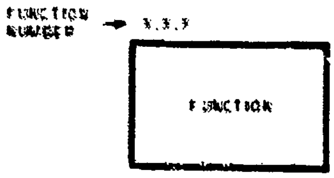

MARSHALING
CONTROL
POINT
RECOVER
AIRCRAFT
MISSION PROFILE
1.15 RECOVER
AIRCRAFT
1.14
TASK FORCE
COURSE
LAUNCH
SW
ESTABLISH
RSHALING POINT
ADING, ALTITUDE
AND A/S
SW
FLY PRESCRIBED
HOLDING
PATTERN
1.14.8 SW
CONFIGURE
AIRCRAFT
FOR RECOVERY
REF
SAME AS
DRAWING
SHEET 2 OF 2
1.16
REF
SW
CEIVE HEADING
ND ALTITUDE
OF HOLDING
PATTERN
SSIGNMENT
SW
VERIFY ATA
AND POSITION
AT HOLDING
POINT
SW
RECEIVE CCA
LANDING
INSTRUCTIONS.
REF
SAME AS
SHEET 2 OF 2
MISSION FUNCTIONS
1.15 RECOVER AIRCRAFT
FIGURE 3 S



MISSION PLAN

LEGEND

A/C	-	AIRCRAFT
ALT	-	ALTITUDE
AMM	-	ANTI-MISSILE MISSILE
A/S	-	AIRSPEED
ASIR	-	AIR SEARCH INFRARED
ETA	-	ESTIMATED TIME OF ARRIVAL
EW	-	EARLY WARNING
FLIR	-	FORWARD LOOKING INFRARED SYSTEM
FLR	-	FORWARD LOOKING RADAR SYSTEM
FOV	-	FIELD OF VIEW
IFF	-	IDENTIFICATION FRIEND OR FOE SYSTEM
IP	-	INITIAL POINT
RHAW	-	RADAR HOMING AND WARNING SYSTEM, E/O
TISEO	-	TARGET IDENTIFICATION SYSTEM
WDS	-	WEAPON DELIVERY SYSTEM



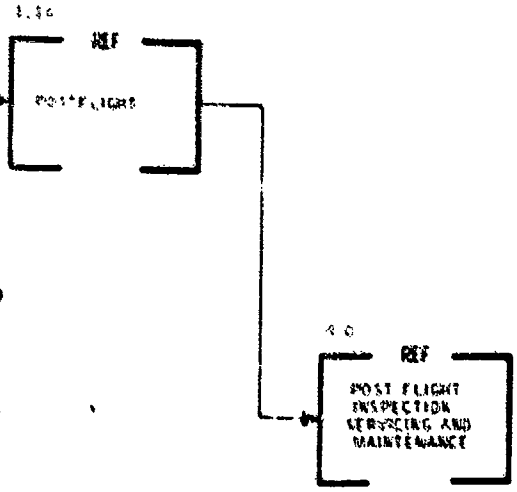


FIGURE 3 SECOND LEVEL FUNCTIONAL FLOW MISSION OPERATIONS - INTERDICTION MISSION - STANDOFF WEAPON ATTACK

yaw information, the majority of the information requirements for a reconnaissance RPA could be derived. This type RPA mission could be developed as an alternative to the first level Reconnaissance Function 1.17 which may include an RPA (directed by the attack aircraft S.O.) containing sensor equipment and mission system. The attack aircraft would perform the launch and also provide the "relay aircraft" function mission.

The Standoff Weapon Scenario contained in Section 1.6 includes several "unplanned" events such as a surface-to-air attack, air-to-air refueling and assignment to a holding pattern to allow for the recovery of damaged aircraft. However, all aircraft systems are assumed to be in a "go" condition from preflight through recovery. All supporting shipboard and airborne systems, such as the Auto Carrier Landing System and CIC are assumed fully operational and in a "go" condition.

1.5.? Weapon Parameters

The Standoff Weapon conceptualized for this mission is based on the range, speed and guidance parameters described in the November 1965 issue of SPACE/AERONAUTICS magazine. The additional parameters are extrapolated from these data. The weapon control options selected for this mission include a zero-zero launch, manual midcourse guidance using the TV sensor for area navigation, visual target acquisition and terminal guidance, in order that the display parameters can be fully exercised. The Standoff Weapon parameters utilized in Scenario No. 2 and depicted in Figure 3 are as follows:

Range: 50-70 nm

Thrust: Constant

Speed: Mach 1.5 to 2.5

Guidance: Hybrid (inertial or manual/TV) with auto-inertial updating by navigational satellite

Control Options:

a) Launch: Visual/manual or blind/auto

b) Midcourse: Visual/manual or visual/auto

c) Terminal: Auto after target aiming point designation, or visual/manual tracking to impact

d) Terminal Autotrackers: Edge seeker, spectral contrast seeker, or E/O correlation seeker

Variable TV Sensor Viewing Parameters:

a) 30° wide-angle option with 45° lateral slew around centerline and 12-1/2° (boresight) to 75° lookdown angle at operator's option.

b) 5° to 10° long range acquisition with 45° lateral slew and 0° (boresight) to 30° lookdown angle at operator's option.

Display: Provides for either a blind launch and midcourse flight utilizing inertial guidance, or a visual launch and midcourse flight using either auto or manual control, or combinations thereof. The VDS displays sensor image and flight status, while the HSD may be slaved to the Standoff Weapon and indicate (weapon) present position on moving map or radar ground mapping display.

Controls: Two hand controllers are provided for control by the S.O. when in manual mode. The right hand controller provides for up/down (pitch) and right/left (yaw) attitude changes similar to the responses to an aircraft control stick. A pushbutton on the top of this control enables manual control when depressed and target designation and subsequent auto control when released. Inadvertent release of the designation pushbutton would not result in a dive maneuver when the FOV lookdown angle is in excess of zero degrees (boresight). The left hand controller provides sensor/boresight alignment in the aft position and directs the sensor field of view (FOV) down to a 75° maximum lookdown angle at the full forward position. Twisting the control handle to the left moves the FOV to a maximum of 45° off-axis to the left and a twisting motion to the right provides a corresponding off-axis to the right view. A spring detent provides pressure to return the control to center and tactile feedback when the sensor optics are on missile lateral centerline. An alternate action thumbswitch provides for changing from 30° (wide angle FOV) to a 5° to 10° (acquisition FOV) angle. If electro/optical zoom is feasible, a thumbwheel in place of the switch would be provided for continuous FOV control. The maximum position in one direction would provide maximum wide angle FOV, while movement to the other extreme position would provide a narrow/long range FOV.

1.6 MISSION SCENARIO NO. 2

The Standoff Weapon Attack developed in this scenario is representative of a type mission which might be planned and executed in support of Naval operations in any theater. In this example, it is assumed that a carrier attack force is committed to support an amphibious assault which has been scheduled to commence within 24 hours of launch. Pre-assault interdiction and air superiority strikes are carried out against the enemy's control centers, airbases, defenses, missile sites, logistics and transportation routes in the assault area to isolate the beachhead. This mission is a daylight attack against a heavily defended, high priority target at maximum a/c range. A realistic fuel safety margin is provided. A Standoff Weapon attack is selected to provide the greatest measure of aircraft survivability. The weather at sea during launch and recovery is forecast to be 10/10 obscured with a ceiling of 500 feet and 1 mile visibility. Weather enroute to the Initial Point and Launch Point is forecast to be 8/10 obscured with the tops of the clouds extending to 12,000 feet. The target area is forecast to be clear with visibility 10 to 15 miles. The terrain between the coast and the target consists of level terrain, low rolling foothills, and several small mountains with elevations to 6,800 feet.

To take advantage of the element of surprise, a low altitude aircraft approach to the weapon launch point has been chosen. The penetration route has been selected so that a low altitude approach can be made using terrain following and terrain avoidance modes to the Initial Point. The target area is expected to be heavily defended by surface-to-air missiles and antiaircraft artillery. A low altitude launch of the weapon with a pop-up maneuver near the target has also been planned to reduce the time the enemy has to acquire the weapon and defend against its delivery. The preplanned weapon launch will be made outside the maximum range of the target area defensive missiles. Because of the vulnerability of the Standoff Weapon aircraft (SW a/c) during penetration, delivery, and escape, an Electronic Counter Measures aircraft (ECM a/c) accompanies the SW a/c as a wingman.

Just prior to this mission, several defense suppression sorties were scheduled to attack SAM sites which are on the route to and from the Standoff Weapon launch point for the high priority target. All of these sorties except one were effective.

One SAM site on the escape route of the SW a/c and ECM a/c remains partially effective and may be capable of a SAM launch. Recognizing the possibility that one or more sorties may incur a distress situation, air-sea rescue and tanker aircraft are standing by just off the coast.

For this mission, it is assumed that programmed automatic flight plan data, profile data and weapon delivery information have been prepared and stored in the airborne computer memory, and that appropriate mission phases will be under automatic control.

Escape from the target area is programmed for minimum altitude after the SW a/c joins up with the ECM a/c. Threat detection equipment is monitored throughout the appropriate mission phases.

The operational sensors utilized during Mission No. 2 are:

a) Forward Looking Radar
b) Forward Looking Infrared
c) RHAW
d) ASIR
e) IFF/SIF
f) High Resolution TV
g) Ground Mapping Radar

The operational weapons that may be employed on Mission No. 2 are:

SW a/c: a) Standoff Weapon/Nuclear Warhead
(Hypothetical system operation described in 1.5.1)
b) Guided Missiles - Air-to-Air (Target Seeking)

ECM a/c: a) Guided Missiles - Anti-Missile Type
b) Guided Missiles - Air-to-Air (Target Seeking)

The following paragraphs detail the crew tasks and operations relative to the Standoff Weapon Mission. The "SW" suffix has been added to those functions which are identical, or similar to, the same first level functions/mission phases occurring in Mission No. 1 Scenario and associated Functional Flow Block Diagram.

Figure 3 presents the second-level functions and flow of the mission operations described herein.

FUNCTION 1.1 SW - PREFLIGHT AIRCRAFT

This function is the same as Mission Scenario No. 1, Function 1.1, Preflight Aircraft.

FUNCTION 1.2 SW - LAUNCH AIRCRAFT

This function is the same as Mission Scenario No. 1, Function 1.2 - Function 1.2 - Launch Aircraft.

FUNCTION 1.3 SW - CLIMB/DEPARTURE

This function is the same as Mission Scenario No. 1, Function 1.3 - Climb/ Departure.

FUNCTION 1.4 SW - CRUISE-OUT

This function is the same as Mission Scenario No. 1, Function 1.4 - Cruise-Out with the following additions:

a) After verifying that the aircraft can perform its primary mission, the pilot verifies that the ECM a/c which is to occupy a wing position and is launched subsequent to the SW a/c, has made contact and is closing from the starboard side.

b) Rendezvous with the ECM a/c is accomplished without incident and both aircraft descend on instruments to the preplanned penetration altitude. Note: Rendezvous procedures used during this phase are described in Function 1.9 SW - Escape.

FUNCTION 1.2 SW - PENETRATE

This function is the same as Mission Scenario No. 1, Function 1.5 - Penetrate.

FUNCTION 1.6 SW - PRE-ATTACK (STANDOFF WEAPON)

Note: Prior to starting Function 1.6, it is assumed that the penetration altitude, airspeed and heading have been established and that the automatic flight program, the Flight Director System and the navigation system are operating satisfactorily.

This mission phase encompasses the approach to the Initial Point (IP), the acquisition of the IP using the on-board sensor display(s), a check on the Flight Director System (FDS) performance, preparation for the attack phase, a break in

stationkeeping by the ECM a/c (wingman), and a pop-up and heading adjustment just prior to the weapon release point. A low level terrain following/terrain avoidance approach to the weapon release point was planned, to minimize the chance for acquisition by ground defensive Early Warning (EW) systems. The pop-up is executed to provide clearance above highest terrain and to insure line-of-sight with the weapon after release.

a) On the approach to the IP, the pilot monitors the mission progress, monitoring the preplanned terrain clearance, heading and airspeed. The pilot verifies that the ECM a/c is maintaining formation.

b) The system operator monitors the mission progress. Based on the flight plan estimated time of arrival (ETA) at the IP, he anticipates its appearance and configures the FLR for acquiring the IP. Upon acquiring the IP, the System Operator (SO) refers to the flight plan coordinates of the IP and compares his present position with the flight plan coordinates, thereby verifying that the FDS is functioning according to plan. A Navigation system update would be made at this time if grid coordinates of the system and the IP did not agree. As the IP is made good on ETA, the SO verifies the new programmed command heading required and the indicated pop-up time. The pilot monitors the FDS pre-launch heading change. The ECM a/c breaks stationkeeping and executes a climb to the preplanned orbit altitude.

c) Upon receiving the pop-up command the pilot manually executes the maneuver to the pre-planned weapon release altitude. Upon reaching the pre-launch attitude the aircraft is leveled-off and a new airspeed is established. The FDS is re-engaged for automatic programmed flight. During the pop-up the SO configured the WDS for the automatic launch of the SW. After configuring the WDS the SO verifies the weapon status and enables the arming switch on the weapon control panel.

While the SW a/c was climbing and establishing the new heading, the ECM a/c climbed above the SW a/c and prepared to establish an orbit and monitor enemy electronic activities for hostile intent or action.

FUNCTION 1.20 - STANDOFF WEAPON ATTACK

This mission phase encompasses the run to the Launch Point, the automatic release of the weapon, the midcourse guidance monitoring of the weapon, a weapon pop-up to provide target acquisition visibility, and terminal tracking or homing of the missile on target. By employing a low level attack with a pop-up maneuver executed approximately 45 seconds prior to weapon arrival on target, hostile reaction time is minimized. The weather in the target area is forecast to be clear, however, on the approach to the target, low broken clouds hanging over the hills will necessitate a "blind" weapon launch.

a) After the pre-launch attitude, heading and airspeed were established, the pilot confirms the WDS selections made by the SO as conforming to the pre-planned attack data. After the confirmation, the pilot enables his weapon arming switch in order to affect release of the weapon. (Two arming "votes" must be set-in for release and weapon detonation). As the run to the Launch Point progresses, the pilot monitors the pre-planned launch heading, altitude, airspeed, and monitors the ASIR and RHAW systems for indication of enemy threat activity.

b) After verifying weapon readiness, the SO verifies that the SW a/c launch-envelope parameters are satisfactory for a successful launch. Since the weapon will be automatically released at a pre-programmed point, the SO monitors the Time-To-Release countdown. The SO also sets the video viewing angle (field of view) on the weapon to a wide angle setting so as to insure that the sensor will be able to pick up the first navigational checkpoint when the weapon breaks into clear air enroute to the target.

c) At the pre-programmed time and position the weapon is automatically released in an auto/inertial mode. Both the pilot and SO verify the weapon release and confirm that a command link to the weapon has been established. Since the weapon was released blind, the SO commands the weapon to transmit a short video test signal to confirm that the video link is also established.

d) After verifying that both the command link and video link are operating satisfactorily, the pilot performs the pre-planned post launch maneuver, climbing slowly to maintain line of sight with the weapon. The SO monitors the video display for indication that the weapon has broken

out into the clear. In anticipation that a course correction may be necessary, the SO configures for manual control. As forecast, the weapon breaks out of the clouds in time to pick up an image of the navigation checkpoint. The SO identifies the checkpoint, verifies that it is the correct point, and prepares to make a course correction if indicated.

e) While the pilot is maintaining a watch for enemy electronic activity and maintaining data link line of sight with the weapon, the SO prepares to command the weapon to execute a pop-up maneuver. The weapon program provides countdown data for this maneuver. When the SO receives the pop-up command, he controls the weapon for execution of the required maneuver. While in the climb, the SO resets the video field of view depression angle so as to maintain an appropriate horizon reference by adjusting the "look-down" angle as the climb/descent angle is changed. While maintaining the optimum (wide angle) field of view, the SO searches for the target area and target.

f) As expected, the SO locates the target area and gross tracking corrections are made, as necessary. A switch to a narrow field of view (FOV) is made to enable detailed evaluation of the target area and acquire the specific aiming point. In the narrow FOV mode, the target and aiming point are positively identified and fine steering corrections are made as necessary to align the weapon on a proper trajectory.

g) At this point, with the weapon properly aimed at the target, the SO has two options. The first option is to continue tracking the aiming point and manually guiding the weapon to impact (detonation). The second option is to select the homing mode, where the target and aiming point is designated for the weapon with the SO monitoring the weapon flight to impact. In this case, it is assumed that the SO selected the manual terminal guidance option, and continues to guide the weapon toward the target. However, with approximately 15 seconds to go, the SO receives a warning that the command and video link signal strengths are deteriorating (due to line-of-sight interference) so he elects to switch to the homing mode for the final terminal guidance and initiates the auto track/seeker mode. Weapon detonation on target was determined.

FUNCTION 1.8 SW - POST ATTACK

This mission phase encompasses a breakaway maneuver after verification of weapon detonation, securing of the WDS, and transmission of the strike report.

a) When the weapon detonated, all signals from the weapon terminated. In the final phase of the terminal guidance the SO was able to monitor the trajectory into the target and verify it was on the aiming point. When transmission terminated the SO configured the WDS safe, and the pilot verified the condition.

b) At this time a breakaway maneuver was executed in the direction of the rendezvous point where the SW a/c will pick up the ECM a/c for a return to the carrier. As the pilot rolls out in the appropriate direction, the SO transmits the strike report to an airborne CIC.

FUNCTION 1.9 SW - ESCAPE

This mission phase encompasses the escape from the target area, rendezvous with the ECM a/c, engagement by an enemy surface to air missile, escape maneuvers, and low altitude flight to the coastout point. Monitoring of the RHAW/ASIR equipment for detection of enemy counteraction is essential during this phase.

a) After executing the breakaway maneuver the FDS provides the pilot with navigation information for rendezvous with the ECM a/c. The ECM a/c, monitoring the strike frequency, notes when the SW a/c has completed the attack. At this time the ECM a/c breaks orbit on the preplanned rendezvous heading. The SW a/c pilot configures sensors and display for station keeping mode and establishes contact with the ECM a/c.

b) Rendezvous is made and the SW a/C slides in on the ECM a/c's wing and maintains this position. This flight element configuration was preplanned since enemy aircraft activity can be expected on the escape route and the ECM a/c is configured with air-to-air missiles and anti-missile-missile (AMM).

c) A descent for a low altitude terrain following maneuver is started. During the descent, enemy SAM activity is detected. While the enemy SAM was searching, no action by either aircraft was initiated but when lock-on/tracking mode signals were detected, the ECM a/c initiated countermeasure activity to break lock and the SW a/c maneuvered to take up a defensive station position and activated onboard ECM equipment.

d) It is assumed that the aircraft were unable to break the SAM track lock and two enemy missiles are launched. The SW a/c monitoring the threat immediately initiates evasive maneuvers while the ECM a/c prepares for and executes an anti-missile attack. After launch of the AAM's against the SAM's, the ECM a/c also tries to evade the missiles by maximum G load maneuvers. The AAM attack on one SAM missile is successful, while the other missile causes moderate damage to the ECM a/c. The SW a/c is not damaged. After assessing the damage it is decided that the SW a/c will assume the lead and the ECM a/c fly on the wing. Sensors and displays on the ECM a/c are configured for stationkeeping and the SW a/c pilot configures for low level flight conditions with reduced airspeed. The SO transmits a battle damage message to the CIC. As the flight is now encountering weather, the SW a/c configures the multimode radar and cockpit display for terrain avoidance mode with the SW a/c in lead and the ECM a/c station keeping on the wing.

e) After the SW a/c assumes lead the activities performed are the same as functions 1.9.3 through 1.9.5 and 1.9.9 through 1.9.13 shown and described in Mission 1 Scenario.

FUNCTION 1.13 SW - CRUISE BACK

This mission phase is the same as Mission Scenario #1, Function 1.13, with the following exceptions:

a) The FDS is maintained in the automatic mode (preprogrammed flight) as the Control Point is reached. At this time the A/C performs the preprogrammed climb maneuver, climbs to the new altitude and establishes heading for the Marshaling Control Point.

b) The ECM a/c breaks stationkeeping upon receipt of clearance for rendezvous and immediate recovery on the carrier due to battle damage.

c) The SW a/c pilot is notified by CIC that a delay in recovery will necessitate air refueling, prior to proceeding to the marshaling control point. After the ECM a/c breaks formation, the SO receives a clearance for change in flight plan and is directed to proceed to the air refueling area.

FUNCTION 1.14 SW - CARRIER RENDEZVOUS

This mission phase encompasses a change in the flight plan, rendezvous with the tanker, air refueling operations, and establishment of a holding pattern at the marshaling control point until cleared to land.

a) After receiving a clearance to proceed to the air refueling area, the SW a/c pilot reconfigures for manual control and starts a climb to a new altitude in preparation for the rendezvous with the tanker aircraft. The new heading and ETA at the refueling area is provided by the FDS by selecting "Refueling Area" as a new flight plan objective. With this data, the pilot establishes the commanded altitude and airspeed (power setting) for tanker rendezvous.

b) While on course for the refueling area, the pilot configures the aircraft sensors and display for acquiring the tanker in preparation for refueling. The SO verifies the ETA at the refueling area where hook-up with the tanker will be made. As the SW a/c approaches the refueling area, the pilot searches for the tanker and verifies that the tanker beacon has been acquired. As the pilot maneuvers the aircraft into refueling position, the SO monitors the communication channel with the tanker and CIC.

c) Upon hook-up with the tanker, the pilot maintains the proper position until refueling is complete, then breaks contact and heads for the marshaling point. While refueling operations are in progress, the SO performs fuel management operations until the required amount of fuel has been transferred.

d) Enroute to the marshaling point, the CIC advises the SW a/c crew that the aircraft is to establish a holding pattern at a pre-determined point referenced to the marshaling control point. The SO acknowledges the message and the pilot establishes a new heading, altitude and airspeed in preparation for entering the assigned holding pattern.

e) At the designated orbit point, verified by the SO, the pilot flys the assigned holding pattern until advised by the CCA to break and descend for recovery and landing. The SO monitors the RHAW/ASIR for threat detection during the time the a/c is in the holding pattern. At this time, the pilot configures the aircraft for recovery. The SO verifies the configuration and acknowledges the CCA message, confirming the crew's understanding of instructions. The aircraft then proceeds to the carrier and enters the landing pattern.

FUNCTION 1.15 SW - RECOVER AIRCRAFT

This mission phase covers the carrier-controlled approach and landing maneuvers from the departure point of the holding pattern to taxi and system shutdown onboard the carrier under instrument flight conditions. The crew functions performed are the same as Function 1.15 - Mission Scenario #1.

FUNCTION 1.16 SW - POST FLIGHT

This function is not developed at the second level, as there are no additional information requirements generated by this function which would be displayed on the VDS.

1.7 INFORMATION REQUIREMENTS ANALYSIS

Following the identification of the second level functions and the allocation of these functions to the pilot and/or Systems Operator for Missions 1 and 2, the Information Requirements (IR) Analysis was initiated. This analysis consisted of the following tasks:

a. Identify specific information required by the pilot and/or the S.O. to accomplish each second-level function identified in Functional Flow Figures 2 and 3.

b. Validate the identified study IR's against similar analyses.

A list of potential information requirements was developed specifically for the VDS study. Other pilot information requirements studies, such as the Northrop P530 study, were reviewed to assure that the preliminary IR list was sufficiently comprehensive. The major categories (flight, navigation, propulsion and configuration) used in JANAIR Report No. 680505[1] were retained to facilitate the subsequent validation task.

Information Requirement Worksheets were prepared for each first-level function (Mission phase). Figure 4 shows an example of a completed worksheet for Function 1.9 - Escape. Each worksheet contained identical listing of candidate items by category. Items preceded by an asterisk were not found in the published IR studies reviewed and may be considered as new items. Each column heading identifies the third digit of the function analyzed and the allocation to the responsible crew member. Fifteen first-level functions were analyzed for Mission No. 1 and 5 first-level functions were analyzed for Mission No. 2. The remaining 10 functions of Mission No. 2 were common to both missions.

Three functions, Takeoff, Cruise and Landing, were used for the preliminary analysis. The pilot IR's were identified by an experienced Human Factors analyst who is a rated jet aircraft pilot with 1,200 flight hours. The System Operator functions were analyzed by a rated bombardier/navigator with over 3000 flight hours and with subsequent experience in Human Factors functions and workload analyses of S.O. crew station duties. The three independently completed worksheets were submitted to another rated System Operator and a second pilot for review. Their reviews identified certain differences in IR identification which necessitated discussion and reconciliation.

INFORMATION REQUIREMENTS WORKSHEET

MISSION: #1 - Interdiction - Bomb Attack

PHASE: Escape - (Low Level)

FIRST LEVEL FUNCTION NO. 1.9.2

INFO. REQMTS: 2ND LEVEL FUNCTION	.1	.2	.3	.4	.5	.6	.7	.8	.9	.10	.11	.12	.13			Σ	Σ
ALLOCATION	P	P	P	P	P	S.O.	S.O.	S.O.	S.O.	S.O.	S.O.	S.O.	S.O.			PILOT	S.O.
FLIGHT INFORMATION Cont'd fr. 1.9.2																	
Attitude - Pitch	P	"	"	"	"											P	
- Roll (SWS Yaw)*	P	"	"	"	"											P	
Pitch Trim																	
*"G" Load																	
Angle of Attack - Actual																	
- Command																	
Altitude - Actual	P	"	"	"	"	S										P	S
- Command	P	"	P	"	"											P	
- Absolute (Radar)	P	"	"	"	"											P	
Vertical Velocity - Actual																	
- Command																	
Airspeed - Actual	P	P	"	"	"	S										P	S
- Command		P		P	"											P	
- Mach Number	P	"	"	"	"											P	
*Time - GMT/Local						S							P				P
Rate of Turn																	
Sideslip																	
Steering - True Heading	P	"	"	"	"											P	
- Heading Command	P	"	P	"	"											P	
- Heading Error																	
- Pitch Command																	
- Roll Command																	
Velocity Vector - Actual																	
Flightpath Deviation (Vertical)																	
Flightpath Deviation (Lateral)																	
Distance Along Runway																	
*Acceleration																	
Waveoff - Command																	
Pullup - Command		P	"	"	"												
*Terrain Avoidance - Flt. Parameters	P	"	"	"	"											P	
*Terrain Following - Flt. Parameters																	
*Station Keeping																	
NAVIGATION INFORMATION																	
Heading						P			P			P					P
Ground Track												S	S				S
Course						P			P			P	S				P
Groundspeed												P	P				P
Aircraft Position - Geo. Ref.						P			P			P					P
- Mission Ref.						S			S			S	P				P
*Bearing to Objective						P			P			S					
Range to Objective						P			P				P				P
Time to Objective						S			S				P				P
Topographic Obstruction	S	"	"	"	"	S			S			P					P
Dangerous Weather (Loc. Ref.)												S					S
Fuel Quantity												S					S
Fuel Flow Rate																	
*Fuel Range												S					S
*Target or C.P. Loc. - Geo. Ref.						P			P			P					P
- Mission Ref.						S			"								
Carrier or Base Position																	

						S			S			S						S
Carrier or Base Position												S						S
*Alternate Targ[illegible] C.P., or Base Loc.												S						S
[illegible]												S						S
Fuel Quantity												S						S
Fuel Flow Rate																		
*Fuel Range												S						S
*Target or C.P. Loc.-Geo. Ref.						P			P			P						P
- Mission Ref.						S			S			S						S
Carrier or Base Position												S						S
*Alternate Target, C.P., or Base Loc.																		
MISSION DATA																		
*Target Identification Designation - (Aiming Point)																		
*Threat Detection - Type(Air or Gnd)							P	S	"	P	"	"	"					P
- Dir. & Range							P	P	"	P	"	"	"					P
*Aircraft Identification - (IFF)								P										P
*ECM/ECCM Activity								P										P
*Target Assessment (Status)																		
SYSTEM STATUS																		
Warning, Caution & Advisory (BITE)*	S	"	"	"	"	S	"	"	"	"	"	"	"				S	S
WEAPON SYSTEM																		
*Weapon(s) - Arm/Safe						[illegible]												
*Weapon(s) - Select/Status																		
*Delivery Mode Parameters																		
*Weapon Peculiar Parameters																		
PROPULSION SYSTEM																		
RPM	P	"	"	"	"												P	
EGT	P	"	"	"	"												P	
EPR (Thrust)	P	"	"	"	"												P	
*Nozzle Position	S	"	"	"	"												S	
*Oil Pressure	S	"	"	"	"												S	
*Hydraulic Pressure	S	"	"	"	"												S	
*Energy Management Parameters	P	"	"	"	"												P	
*Smoke Abatement																		
CONFIGURATION STATUS																		
Landing Gear Position																		
Speedbrake Position																		
Trailing Edge Flap Position																		
*Leading Edge Flap Position																		
*Wing Sweep Position																		
*Anti Skid System Status																		
Tail Hook (or Drag Chute) Status																		
Electronic & E/O SYSTEMS																		
*RHAW - Select/Status						P				P	"	"	"					P
*ASIR - S/S						P				P	"	"	"					P
*IFF/SIF - S/S																		
*TISEO - S/S																		
*ECCM - S/S																		
*Passive Sensor Systems - S/S										P	"	"	"					P
*Active Sensor System - S/S	P	"	"	"	"						P						P	P
*Voice Warning System - S/S	P	"	"	"	"	P	"	"	"	"	"	"	"				P	P
COMM. & NAV. AID SYSTEMS																		
*UHF Radio - Select/Status																		
*VHF Radio - S/S																		
*Intercomm. - S/S	P				P	P						P	P				P	P
*Tacan - S/S																		
*Omni/ILS/Auto. Carrier Land. Sys.-S/S																		
*Satellite Comm. Chan. - S/S													P					P
*Nav. System/Omega - S/S						P						P	"					[illegible]
*Tact. Comm. & Control - S/S																		

FIGURE 4 INFORMATION REQUIREMENTS WORKSHEET [illegible]

[illegible]						P						P	"					P
*Tact. Comm. & Control - S/S																		
Warning, Caution & Advisory (BITE)*	S	P	"	"	"	S	"	"	"	"	"	"	"				S	S
WEAPON SYSTEM																		
*Weapon(s) - Arm/Safe						SW												
*Weapon(s) - Select/Status																		
*Delivery Mode Parameters																		
*Weapon Peculiar Parameters																		
PROPULSION SYSTEM																		
RPM	P	"	"	"	"												P	
EGT	P	"	"	"	"												P	
EPR (Thrust)	P	"	"	"	"												P	
*Nozzle Position	S	"	"	"	"												S	
*Oil Pressure	S	"	"	"	"												S	
*Hydraulic Pressure	S	"	"	"	"												S	
*Energy Management Parameters	P	"	"	"	"												P	
*Smoke Abatement																		
CONFIGURATION STATUS																		
Landing Gear Position																		
Speedbrake Position																		
Trailing Edge Flap Position																		
*Leading Edge Flap Position																		
*Wing Sweep Position																		
*Anti Skid System Status																		
Tail Hook (or Drag Chute) Status																		
Electronic & E/O SYSTEMS																		
*RHAW - Select/Status						P				P	"	"	"					P
*ASIR - S/S						P				P	"	"	"					P
*IFF/SIF - S/S																		
*TISEO - S/S																		
*ECCM - S/S																		
*Passive Sensor Systems - S/S										P	"	"	"					P
*Active Sensor System - S/S	P	"	"	"	"						P						P	P
*Voice Warning System - S/S	P	"	"	"	"	P	"	"	"	"	"	"	"				P	P
COMM. & NAV. AID SYSTEMS																		
*UHF Radio - Select/Status																		
*VHF Radio - S/S																		
*Intercomm. - S/S	P				P	P						P	P				P	P
*Tacan - S/S																		
*Omni/ILS/Auto. Carrier Land. Sys.-S/S																		
*Satellite Comm. Chan. - S/S													P					P
*Nav. System/Omega - S/S						P						P	"					P
*Tact. Comm. & Control - S/S																		
*LIFE SUPPORT SYSTEM																		
*Oxygen Flow & Quantity - S/S																		
*Cabin Pressure - S/S																		
*Windshield/Canopy - Anti-Ice - S/S																		
*Anti-Rain (Windshield) - S/S																		
*OTHER A/C SYSTEMS																		
*Ext. Nav., Refuelg.& Form. Lts. - S/S																		
*Landing Light Position - S/S																		
*Internal Lights - S/S																		
*Stability Augmentation - S/S	P	"	"	"	"												P	
*Auto Pilot - S/S																		

*Information not identified in referenced studies.

FIGURE 4 INFORMATION REQUIREMENTS WORKSHEET SAMPLE

The differences in IR item identification were found to be primarily due to semantic difficulties in two areas. First, opinions differed as to the pilot's requirements for error vs command, or actual (status) information. It was determined that the terms: actual, command and error reflect display/control terminology and either have not been defined in terms of information requirements, or consistently applied, in some previous studies. The following definitions were used in this study to alleviate this problem:

1. Command Information: That data which is an index of desired performance of a system or subsystem, the parameters of which are derived from the systems mission requirements.
2. Actual Information: That data which is an index of the current status of the system or subsystem, and is independent of command information.
3. Error Information: That data which is an index of the discrepancies or difference between command information indices and actual information indices.

The second area of concern was the concept of necessary and sufficient information. The differences identified were primarily in the "sufficient" category (rather than necessary) and pertained to backup information which would aid in the decision making process, or add confidence to that decision. When the minor semantic differences were resolved, the data reflected significantly increased inter-rater consensus.

An iteration was then conducted where the information requirements were coded Primary (P) and Secondary (S). It was found that in the three functions analyzed, there were no areas of disagreement between analyst's ratings for those items identified as "primary" information requirements. The remaining 17 functions were then analyzed using Primary and Secondary coding. All of the worksheets for Mission 1 and 2 functions were completed by the Human Factors analysts and then reviewed by another pilot and Bomb/Nav System operator. Minor discrepancies between the ratings were then resolved.

The Information Requirements Summary for Mission No. 1 is shown in Table 1, sheets 1, 2 and 3. Table 2 contains the summary of the information requirements identified for Mission No. 2, Standoff Weapon Attack.

INFORMATION REQUIREMENTS SUMMARY (S[illegible] 1 of 3)

MISSION NO. 1 - AIR-TO-AIR ATTACK

FUNCTION/PHASE NO.		1.10		1.11		1.12						∑	∑
	ALLOCATION	P	S O	P	S O	P	S O					P	S O
FLIGHT INFORMATION													
Attitude	- Pitch	P		P		P						P	
	- Roll (SWS Yaw)*	P		P		P						P	
Pitch Trim												P S	
"G" Load				P								P	
Angle of Attack	- Actual	S										P S	
	- Command												
Altitude	- Actual	P		P		P						P	S
	- Command			P								P	
	- Absolute (Radar)	P										P	
Vertical Velocity	- Actual	S										P S	
	- Command												
Airspeed	- Actual	P		P								P	P S
	- Command			P								P	P
	- Mach Number	P		P								P	
*Time	- GMT/Local											S	P S
Rate of Turn												P	P
Sideslip													
Steering	- True Heading	P										P S	
	- Heading Command	P		P								P	
	- Heading Error			P								P S	P
	- Pitch Command											P	
	- Roll Command											P	
Velocity Vector	- Actual											P	P
Flightpath Deviation (Vertical)												P	P
Flightpath Deviation (Lateral)												P	P
Distance Along Runway													
*Acceleration													
Waveoff	- Command											P	P
Pullup	- Command											P	
*Terrain Avoidance	- Flt. Parameters											P	
*Terrain Following	- Flt. Parameters											P	
*Station Keeping													
NAVIGATION INFORMATION													
Heading													P
Ground Track													P S
Course													P S
Groundspeed													P
Aircraft Position	- Geo. Ref.												P S
	- Mission Ref.											S	P S
*Bearing to Objective			P	P								P	P S
Range to Objective			P	P								P S	P S
Time to Objective												P S	P S
Topographic Obstruction												P S	P
Dangerous Weather (Loc. Ref.)													S
Fuel Quantity						S	P					S	P S
Fuel Flow Rate						P						P S	S
*Fuel Range							S					P S	P S
*Target or C.P. Loc.	-Geo. Ref.												P S
	- Mission Ref.											S	P S
Carrier or Base Position												S	P
*Alternate Target, C.P., or Base Loc.												S	S
MISSION DATA													

MISSION DATA																	
Target Identification				S	P											S	P
[illegible]																	P S
[illegible]																	P
Alternate Target [illegible]																	S
MISSION DATA																	
Target Identification				S	P											S	P
Designation [illegible]				P	P											P	P
Threat Detection - Type [illegible]								P								S	P S
- Dir., Range		P		P												P	P
Aircraft Identification (IFF)				S	P											S	P
[illegible] Network																	P
Target Assessment Status							P	P								P	P
SYSTEM STATUS																	
Warning, Caution, Advisory [illegible]	S	S		S	S		S	(P)*								(P) S	(P) S
WEAPON SYSTEM																	
Weapon [illegible]		P					S	P								P S	P
Weapon [illegible]		P					S	P								P S	P S
Delivery Mode Parameters		S		P												P	S
Weapon [illegible] Parameters		S		P				P								P S	P S
PROPULSION SYSTEM																	
[illegible]	P			P			P									P	
[illegible]	P			P			P									P	
[illegible]	P			P			P									P	
[illegible]	S			S			P									P S	
[illegible]	S						P									P S	
[illegible]																P	
[illegible]																P	
[illegible] Statement				P			P									P	
CONFIGURATION STATUS																	
Landing [illegible]																P	S
Speed Brake [illegible]																P	
Trailing Edge Flap [illegible]																P	
Leading Edge Flap [illegible]																P	
Wing Sweep [illegible]																P	
[illegible] System Status																	
[illegible]																P	S
ELECTRONIC & E/O SYSTEMS																	
[illegible]								P									P
[illegible]								P									P
IFF [illegible]					P												P
[illegible]					P												P
[illegible]								P									P
[illegible]								P									
[illegible]																	P
[illegible]								P									
COMM & NAV AID SYSTEMS																	
[illegible]																	P
LIFE SUPPORT SYSTEM																	

[illegible]																	
[illegible]								P									
[illegible]																	
[illegible]				P												P	
[illegible]								P								P	P
PROPULSION SYSTEM																	
[illegible]				P												P	
[illegible]	P			P			P									P	
[illegible]							P									P	
[illegible]							P									P	
[illegible]							P									P	
[illegible]																P	
[illegible]																P	
[illegible]				P			P									P	
CONFIGURATION STATUS																	
Landing Gear Position																P	S
Speed Brake Position																P	
Trailing Edge Flap Position																P	
Leading Edge Flap Position																P	
Wing Sweep Position																P	
[illegible]																	
[illegible]																P	
ELECTRONIC & E/O SYSTEMS																	
[illegible]		P						P									P
[illegible]		P						P									P
[illegible]		P			P												P
[illegible]		P			P												P
[illegible]								P									P
[illegible]		P						P									P
[illegible]	P	P		P			P									P	P
[illegible]		P		P	P		P	P								P	P
COMM. & NAV AID SYSTEMS																	
[illegible]																P	P
[illegible]																	
[illegible]		P		P	P		P	P								P	P
[illegible]																	
[illegible]																	
[illegible]																	P
[illegible]																	P
[illegible]								P									P
LIFE SUPPORT SYSTEM																	
[illegible]					P		P	P								P	P
[illegible]					P		P	P								P	
[illegible]							P										
[illegible]																	
OTHER A/C SYSTEMS																	
[illegible]																	
[illegible]																	
[illegible]																	
[illegible]																	
[illegible]																	

MISSION NO. [illegible]

FUNCTION PHASE [illegible]

ALLOCATION

FLIGHT INFORMATION

NAVIGATION INFORMATION

Dangerous Weather (Loc. Ref.)					S						S			
Fuel Quantity					S		S	S		S				
Fuel Flow Rate							S	S		P				
*Fuel Range					S			P		S	P			
*Target or C.P. Loc.-Geo. Ref.					P			S						
- Mission Ref.					S		S	P						
Carrier or Base Position					S			P		S	P		S	
*Alternate Target, C.P., or Base Loc.								S		S				
MISSION DATA														
*Target Identification														
Designation - (Aiming Point)														
*Threat Detection - Type (Air or Gnd)					P									
- Dir. & Range					P									
*Aircraft Identification - (IFF)					P									
*ECM/ECCM Activity					P									
*Target Assessment (Status)	P	P												
SYSTEM STATUS														
Warning, Caution & Advisory (BITE)*	S	S		S	S		S	S		S	S		S	
WEAPON SYSTEM														
*Weapon(s) - Arm/Safe	S	P									P			
*Weapon(s) - Select/Status		S									P			
*Delivery Mode Parameters														
*Weapon Peculiar Parameters	P	P												
PROPULSION SYSTEM														
RPM	P			P			P			P			P	
EGT	P			P			P			P			P	
F (Thrust)	P			P			P			P			P	
*Nozzle Position	S						S			S			S	
*Oil Pressure	S			S			S			S			S	
*Hydraulic Pressure	S			S			S			S			S	
*Energy Management Parameters				P			S			S				
*Smoke Abatement	P													
CONFIGURATION STATUS														
Landing Gear Position										P	S		P	
Speedbrake Position										P			P	
Trailing Edge Flap Position										P			P	
*Leading Edge Flap Position										P			P	
*Wing Sweep Position							P			P	S		P	
*Anti Skid System Status														
Tail Hook (or Drag Chute) Status										P	S			
ELECTRONIC & E/O SYSTEMS														
*RHAW - Select/Status					P			P			P			
*ASIR - S/S					P			P			P			
*IFF/SIF - S/S														
*TISEO - S/S														
*ECCM - S/S														
*Passive Sensor Systems - S/S					P						P			
*Active Sensor System - S/S				P	P					S	P		P	
*Voice Warning System - S/S	P	P		P	P		P	P		P	P		P	
COMM. & NAV. AID SYSTEMS														
*UHF Radio - Select/Status								P		S	P		P	
*VHF Radio - S/S		P												
*Intercom. - S/S	P	S		P	P		P	P		P	P		P	
*Tacan - S/S														
*Omni/ILS/Auto. Carrier Land. Sys-S/S														
*Satellite Comm. Chan. - S/S					P						P			
*Nav. System Omega - S/S					P						P			

*Nav. System Omega - S/S					P						P			

SYSTEM STATUS														
Warning, Caution & Advisory (BIT)*	S	S		S	S		S	S		S	S		S	
WEAPON SYSTEM														
*Weapon(s) - Arm/Safe	S	P									P			
*Weapon(s) - Select Status		S									P			
*Delivery Mode Parameters														
*Weapon Peculiar Parameters	P	P												
PROPULSION SYSTEM														
RPM	P			P			P			P			P	
EGT	P			P			P			P			P	
[illegible]	P			P			P			P			P	
*Nozzle Position	S			S			S			S			S	
*Oil Pressure	S			S			S			S			S	
*Hydraulic Pressure	S			S			S			S			S	
*Energy Management Parameters				P			S			S				
*Smoke Abatement	P													
CONFIGURATION STATUS														
Landing Gear Position										P	S		P	
Speedbrake Position										P			P	
Trailing Edge Flap Position										P			P	
*Leading Edge Flap Position										P			P	
*Wing Sweep Position							P			P	S		P	
*Anti Skid System Status														
Tail Hook (or Drag Chute) Status										P	S			
ELECTRONIC & E/O SYSTEMS														
*RHAW - Select/Status					P			P			P			
*ASCR - S/S					P			P			P			
*IFF/SIF - S/S														
*TISEO - S/S														
*ECM - S/S														
*Passive Sensor Systems - S/S					P						P			
*Active Sensor System - S/S				P	P					S	P		P	
*Voice Warning System - S/S	P	P		P	P		P	P		P	P		P	
COMM. & NAV. AID SYSTEMS														
*UHF Radio - Select/Status								P		S	P		P	
*VHF Radio - S/S		P												
*Intercomm. - S/S	P	S		P	P		P	P		P	P		P	
*Tacan - S/S														
*Omni/ILS/Auto. Carrier Land. Sys. - S/S														
*Satellite Comm. Chan. - S/S					P						P			
*Nav. System Omega - S/S					P						P			
*Tact. Comm. & Control - S/S		P					S	P		S	P		P	
LIFE SUPPORT SYSTEM														
*Oxygen Flow & Quantity - S/S							S							
*Cabin Pressure - S/S							S							
Windshield/Canopy - Anti-Ice - S/S														
*Anti-Rain (Windshield) - S/S										P			P	
OTHER A/C SYSTEMS														
*Ext. Nav., Refuel. & Form. Lts. - S/S										P				
*Landing Light Position - S/S														
*Internal Lights - S/S														
*Stability Augmentation - S/S	P			P			P			P			P	
*[illegible] - S/S														

MISSION NO 1 BOMB ATTACK

FUNCTION

ALLOCATION P S O

FLIGHT INFORMATION

Altitude

Airspeed

Rate of Turn

Sideslip

Steering

NAVIGATION INFORMATION

Course

Aircraft Position

Range to Objective

Time to Objective

Best Available Copy

Flightpath Deviation (Vertical)																P	
Flightpath Deviation (Lateral)																	
Distance Along Runway																	
*Acceleration																	
Waveoff - Command																	
Pullup - Command										P						P	
*Terrain Avoidance - Flt. Parameters										P			P				
*Terrain Following - Flt. Parameters																	
*Station Keeping																	
NAVIGATION INFORMATION																	
Heading		P			P			P			P			P			
Ground Track					S						P			S			
Course					P			P			S			S			
Groundspeed					P			P			P						
Aircraft Position - Geo. Ref.		P			S			P			P			P			
- Mission Ref.		P			P			S		S	S			S			
*Bearing to Objective					P			S			P			P		P	S
Range to Objective					P			S			P			P		P	S
Time to Objective					P		S	P		S	P			P		P	S
Topographic Obstruction								S		S	P			P		P	S
Dangerous Weather (Loc. Ref.)																	
Fuel Quantity							S	P									
Fuel Flow Rate	P			S			S	P									
*Fuel Range							P	P									
*Target or C.P. Loc.-Geo. Ref.		P			S			P			P			P			
- Mission Ref.		P			P			P		S	S			S			
Carrier or Base Position		P															
*Alternate Target, C.P., or Base Loc.																	
MISSION DATA																	
*Target Identification														P		P	P
Designation - (Aiming Point)																P	P
*Threat Detection - Type (Air or Gnd)																	P
- Dir. & Range																	
*Aircraft Identification - (IFF)																	
*ECM/ECCM Activity																	P
*Target Assessment (Status)																	
SYSTEM STATUS																	
Warning, Caution & Advisory (BITE)*	S	S		S	S		(P)*	(P)*		S	S		S	S		S	S
WEAPON SYSTEM																	
*Weapon(s) - Arm/Safe													P	P		S	
*Weapon(s) - Select/Status							P	S					P	P		S	P
*Delivery Mode Parameters														S		P	
*Weapon Peculiar Parameters														S		S	
PROPULSION SYSTEM																	
RPM	P			P			P			P			P			P	
EGT	P			P			P			P			P			P	
EPR (Thrust)	P			P			P			P			P			P	
*Nozzle Position	P			S			S			S			S			S	
*Oil Pressure	P			S			S			S			S			S	
*Hydraulic Pressure	P			S			S			S			S			S	
*Energy Management Parameters				P			S			S			S				
*Smoke Abatement													P			P	
CONFIGURATION STATUS																	
Landing Gear Position	P	S															
Speedbrake Position	P																
Trailing Edge Flap Position	P																
*Leading Edge Flap Position	P																

*Leading Edge Flap Position	P																
*Wing Sweep Position	P	S															
WEAPON SYSTEM																	
*Weapon(s) - Arm/Safe													P	P		S	
*Weapon(s) - Select/Status							P	S					P	P		S	P
*Delivery Mode Parameters														S		P	
*Weapon Peculiar Parameters														S		S	
PROPULSION SYSTEM																	
RPM	P			P			P			P			P			P	
EGT	P			P			P			P			P			P	
EPR (Thrust)	P			P			P			P			P			P	
*Nozzle Position	P			S			S			S			S			S	
*Oil Pressure	P			S			S			S			S			S	
*Hydraulic Pressure	P			S			S			S			S			S	
*Energy Management Parameters				P			S			S			S				
*Smoke Abatement													P			P	
CONFIGURATION STATUS																	
Landing Gear Position	P	S															
Speedbrake Position	P																
Trailing Edge Flap Position	P																
*Leading Edge Flap Position	P																
*Wing Sweep Position	P	S															
*Anti Skid System Status																	
Tail Hook (or Drag Chute) Status	P	S															
ELECTRONIC & E/O SYSTEMS																	
*RHAW - Select/Status							S	P		S	P						P
*ASIR - S/S							S	P		S	P						P
*IFF/SIF - S/S							S	P									
*TISEO - S/S							S	P									
*ECCM - S/S								P									
*Passive Sensor Systems - S/S							S	P			P			P			P
*Active Sensor System - S/S							S	P		P	P		P	P		P	P
*Voice Warning System - S/S	P	P		P	P		P	P		P	P		P	P		P	P
COMM. & NAV. AID SYSTEMS																	
*UHF Radio - Select/Status	P	P		P	P												
*VHF Radio - S/S	P	P		P	P		P	F		P	P		P	P		P	P
*Intercomm. - S/S																	
*Tacan - S/S																	
*Omni/ILS/Auto. Carrier Land. Sys.-S/S																	
*Satellite Comm. Chan. - S/S					P												
*Nav. System/Omega - S/S											P						
*Tact. Comm. & Control - S/S	P	P		S	P		S	S									
***LIFE SUPPORT SYSTEM**																	
*Oxygen Flow & Quantity - S/S																	
*Cabin Pressure - S/S																	
*Windshield/Canopy - Anti-Ice - S/S																	
*Anti-Rain (Windshield) - S/S																	
***OTHER A/C SYSTEMS**																	
*Ext. Nav., Refuelg.& Form. Lts. - S/S																	
*Landing Light Position - S/S																	
*Internal Lights - S/S																	
*Stability Augmentation - S/S	P			P			P			P			P			P	
*Auto Pilot - S/S																	

*Information not identified in referenced studies.

TABLE II INFORMATION REQUIREMENTS SUMMARY

MISSION NO. 2 - STANDOFF WEAPON ATTACK

FUNCTION/PHASE NO.		1.6 SW		1.20		1.8 SW		1.9 SW		1.14 SW		∑	∑
	ALLOCATION	P	SO	P	SO**	P	SO	P	SO	P	SO	P	SO
FLIGHT INFORMATION													
Attitude	- Pitch	P		P	wP	P		P		P		P	wP
	- Roll (SWS Yaw)*	P		P	w(P)*	P		P		P		P	w(P)*
Pitch Trim		P								P		P	
*"G" Load								P				P	
Angle of Attack	- Actual							S		P		P S	
	- Command												
Altitude	- Actual	P		P	wP	P		P		P		P	wP
	- Command	P		P	wP			P		P		P	wP
	- Absolute (Radar)							P				P	
Vertical Velocity	- Actual												
	- Command											P	
Airspeed	- Actual	P		P		P		P		P		P	
	- Command	P		P						P		P	
	- Mach Number	P		P		P		P		P		P	
*Time	- GMT/Local	P	S		S						P	P	P S
Rate of Turn				P		S				P		P S	
Sideslip													
Steering	- True Heading	P		P	wP			P		P		P	wP
	- Heading Command	P	P		wP			P				P	P wP
	- Heading Error												
	- Pitch Command	P										P	
	- Roll Command												
Velocity Vector	- Actual												
Flightpath Deviation (Vertical)					wS								wS
Flightpath Deviation (Lateral)					wS								wS
Distance Along Runway													
*Acceleration													
Waveoff	- Command												
Pullup	- Command												
*Terrain Avoidance- Flt. Parameters		P						P				P	
*Terrain Following- Flt. Parameters													
*Station Keeping		P						P		P		P	
NAVIGATION INFORMATION													
Heading			S		P wP						P		P wP
Ground Track			S										S
Course											S		S
Groundspeed											P		P
Aircraft Position	- Geo. Ref.		P		wP					S	P	S	P wP
	- Mission Ref.		P		wP								P wP
*Bearing to Objective			P		wS					S	P	S	P wS
Range to Objective					wS					S	P	S	P wS
Time to Objective			P	P	wP					S	P	P S	P wP
Topographic Obstruction					wS								
Dangerous Weather (Loc. Ref.)													
Fuel Quantity								S	P	S	P	S	P
Fuel Flow Rate													
*Fuel Range											P		P
*Target or C.P. Loc.-Geo. Ref.			P		wP						P		P wP

- Mission Ref.		P			wP												P wP
Carrier or Base Position																	
Topographic Obstruction					wS												
Dangerous Weather (Loc. Ref.)																	
Fuel Quantity										S	P		S	P		S	P
Fuel Flow Rate																	
*Fuel Range														P			P
*Target or C.P. Loc.-Geo. Ref.		P			wP									P			P wP
- Mission Ref.		P			wP												P wP
Carrier or Base Position														P			P
*Alternate Target, C.P., or Base Loc.					wS									P			P wS
MISSION DATA																	
*Target Identification					P												P
Designation - (Aiming Point)					P												P
*Threat Detection - Type(Air or Gnd)										P						P	
- Dir. & Range										P						P	
*Aircraft Identification - (IFF)																	
*ECM/ECCM Activity																	
*Target Assessment (Status)					P			P									P
SYSTEM STATUS																	
Warning, Caution & Advisory (BITE)*	S	S		S			S	S		S	(P)*		S	S		S	(P)*S
WEAPON SYSTEM																	
*Weapon(s) - Arm/Safe		P		P	wS		S	P								P S	P wS
*Weapon(s) - Select/Status		P		P	wP		S	S								P S	P wP
*Delivery Mode Parameters		P			P												P
*Weapon Peculiar Parameters	P	P			P			P								P	P
PROPULSION SYSTEM																	
RPM	P			P			P			P			P			P	
EGT	P			P			P			P			P			P	
EPR (Thrust) (SwS Thrust)*	P			P	w(P)		P			P			P			P	w(P)
*Nozzle Position	S			S			S			P			S			P S	
*Oil Pressure	S			S			S			P			S			P S	
*Hydraulic Pressure	S			S			S			P			S			P S	
*Energy Management Parameters	S						S			S			S			S	
*Smoke Abatement																	
CONFIGURATION STATUS																	
Landing Gear Position													P	S		P	S
Speedbrake Position													P	S		P	S
Trailing Edge Flap Position													P	S		P	S
*Leading Edge Flap Position													P	S		P	S
*Wing Sweep Position										P			P	S		P	S
*Anti Skid System Status																	
Tail Hook (or Drag Chute) Status													P	S		P	S
ELECTRONIC & E/O SYSTEMS																	
*RHAW - Select/Status				P						S	P			S		P S	P S
*ASIR - S/S				P						S	P			S		P S	P S
*IFF/SIF - S/S										S	S		S	P		S	P S
*TISEO - S/S											S			S			S
*ECCM - S/S										S	P					S	P
*Passive Sensor Systems - S/S					wP						P			S			P wP
*Active Sensor System - S/S	P	P		S						P	S		P	P		P S	P
*Voice Warning System - S/S	P	P		P	P		P	P		P	P		P	P		P	P
COMM. & NAV. AID SYSTEMS																	
*UHF Radio - Select/Status										P			S	P		P S	P
*VHF Radio - S/S							S	P			P					S	P
*Intercomm. - S/S	P	P		P	P		P	P		P	P		P	P		P	P
*Tacan - S/S																	
*Omni/ILS/Auto. Carrier Land. Sys.-S/S																	
*Satellite Comm. Chan. - S/S											S			P			P S

[illegible] - S/S											S			P			P S
*Nav. System/Omega - S/S											S			P			P S
[illegible]	[illegible]	S		S			S	S		S	(P)*		S	S		S	(P)*S
WEAPON SYSTEM																	
*Weapon(s) - Arm/Safe		P		P	wS		S	P								P S	P wS
*Weapon(s) - Select/Status		P		P	wP		S	S								P S	P wP
*Delivery Mode Parameters		P			P												P
*Weapon Peculiar Parameters	P	P			P			P								P	P
PROPULSION SYSTEM																	
RPM	P			P			P			P			P			P	
EGT	P			P			P			P			P			P	
EPR (Thrust) (SwS Thrust)*	P			P	w(P)		P			P			P			P	w(P)
*Nozzle Position	S			S			S			P			S			P S	
*Oil Pressure	S			S			S			P			S			P S	
*Hydraulic Pressure	S			S			S			P			S			P S	
*Energy Management Parameters	S						S			S			S			S	
*Smoke Abatement																	
CONFIGURATION STATUS																	
Landing Gear Position													P	S		P	S
Speedbrake Position													P	S		P	S
Trailing Edge Flap Position													P	S		P	S
*Leading Edge Flap Position													P	S		P	S
*Wing Sweep Position										P			P	S		P	S
*Anti Skid System Status																	
Tail Hook (or Drag Chute) Status													P	S		P	S
ELECTRONIC & E/O SYSTEMS																	
*RHAW - Select/Status				P						S	P			S		P S	P S
*ASIR - S/S				P						S	P			S		P S	P S
*IFF/SIF - S/S										S	S		S	P		S	P S
*TISEO - S/S											S			S			S
*ECCM - S/S										S	P					S	P
*Passive Sensor Systems - S/S					wP						P			S			P wP
*Active Sensor System - S/S	P	P		S						P	S		P	P		P S	P
*Voice Warning System - S/S	P	P		P	P		P	P		P	P		P	P		P	P
COMM. & NAV. AID SYSTEMS																	
*UHF Radio - Select/Status										P			S	P		P S	P
*VHF Radio - S/S							S	P			P					S	P
*Intercomm. - S/S	P	P		P	P		P	P		P	P		P	P		P	P
*Tacan - S/S																	
*Omni/ILS/Auto. Carrier Land. Sys.-S/S																	
*Satellite Comm. Chan. - S/S											S			P			P S
*Nav. System/Omega - S/S											S			P			P S
*Tact. Comm. & Control - S/S								P			P			P			P
***LIFE SUPPORT SYSTEM**																	
*Oxygen Flow & Quantity - S/S																	
*Cabin Pressure - S/S										P	S					P	S
*Windshield/Canopy - Anti-Ice - S/S																	
*Anti-Rain (Windshield) - S/S																	
***OTHER A/C SYSTEMS**																	
*Ext. Nav., Refuelg.& Form. Lts. - S/S																	
*Landing Light Position - S/S																	
*Internal Lights - S/S																	
*Stability Augmentation - S/S	P			P			P			P			P			P	
*Auto Pilot - S/S	P			P			P			P						P	

*Information not identified in referenced studies.

**wP or wS - S. Weapon Primary or Secondary information/parameters.

The last two columns in each table summarize the information required by the Pilot and the S.O. for each mission. Only the highest (primary) ratings are shown in the summary columns for information items identified as both P and S within a mission phase.

No significant differences were found between the primary information requirements for the semiautomatic man/machine system mode of operation used in Mission No. 1, or in the automatic system mode postulated for Mission No. 2 where the operators performed monitoring/system manager functions. This can be understood when one considers the roles that the human operator plays in the manual and automatic modes. In both instances he must be constantly aware of the effectiveness of the vehicle control commands. The pilot needs to be aware of the status and trends of the system on a relatively continuous basis. The information he requires is the same whether he is in the loop as a controller, or whether he serves only as a monitor of system functions being controlled by a servomechanism.

1.7.1 Information Requirements Validation

As noted in section 1.7, the concluding task of this study phase is the comparison of the Information Requirements identified for the 1985 attack aircraft with those IR's identified in previous studies.

In the JANAIR Report cited previously (ref. 2 , page 27) the authors state that:

> "It is necessary to point out the dissimilarities among the studies cited from which we have made a generalization. That is, we are guilty to some extent of comparing apples and oranges in that not all the IR studies are alike in their method and their purpose. Some apply to a certain class of aircraft, some apply to just one aircraft, and some apply to a particular display concept which may be used in more than one aircraft."

To guard against this problem to the maximum extent possible, the information requirements studies selected for comparison with the results of the VDS study IR's met one or more of the following constraints:

a. an attack aircraft is postulated for the mission,
b. an interdiction (air-to-ground attack) mission was flown, and
c. the information requirements were identified preceding display design.

Within the time constraints imposed on this study, only five IR analyses were available which met the selection criteria. These were:

1. The DAC/ANIP study conducted by Dunlap and Associates which met criteria c.(3)
2. The Grumman Aircraft study on Recommended Pilot Displays which met criteria a and partially, b.(4)
3. The Hughes Aircraft studies of tactical aircraft displays.(5) One of these studies (TAC #15) met all selection criteria.
4. The other study (TAC #14) met a and c. (Personal communication with the author.)
5. The unpublished Northrop/Aircraft Division P530 Information Requirements Study which met b and c criteria.

In addition to the data from these studies, the JANAIR Report information requirements summary data are included for comparison. Although the authors saw fit to drop the distinction between command, status and error information they pointed out that: "It seems sufficient to indicate what information is required without becoming embroiled in the question of what form in which it is to be presented" (ref. 2, page 33). In regard to the data obtained in the VDS IR study phase and also shown in the referenced studies, it is difficult to accept their rationalization for deleting the form (or manner of presentation) while retaining only the content. However, for comparative purposes, the JANAIR IR summary data have been extracted from Table 14, VDS Information Requirements and Table 15, HSD Information Requirements using M, D and O coding for their Mandatory, Desirable and Optional classifications. These data are included in the matrix as their composite list recommendations are based on 6 studies for the Takeoff and Enroute phases, and 16 studies for the Landing phase.

Tables 3, 4 and 5, following, present the IR data from the referenced studies, the VDS study, and indicate the agreement (√) between a VDS information item and an item as identified in one or more of the referenced studies. Information items with asterisks are additional items to those identified in the JANAIR report; therefore no comparison could be made between the VDS study data and the JANAIR referenced studies.

Table 3 presents the information items identified for the Takeoff phase. Thirty-three VDS items agree with one or more previously identified items, while there was disagreement on 11 items. The items on which there was disagreement include the flight control parameters of yaw and velocity vector. Also, there were three instances of differences between "command" or "actual" information to be provided for Flight Information. The remaining differences are in the Navigation and Configuration Status categories. The latter differences probably reflect the VDS study emphasis on overall information required vs emphasis on Flight Information which appears to prevail in the referenced studies.

Table 4, Enroute Phase, shows a higher level of inter-item agreement between all of the studies than was the case for the Takeoff phase. Thirty-three items identified in the VDS study were in agreement with the referenced studies, while only 7 items were in disagreement. These include 6 Flight Information items: yaw, bank, rate of turn, sideslip and velocity vector and again, 1 difference between "Command" appeared.

TABLE 3 TAKEOFF PHASE - INFORMATION REQUIREMENTS COMPARISON MATRIX

IDENTIFIED INFORMATION REQUIREMENTS		DAC/ANIP	GRUMMAN ATT. A/C	HUGHES TAC #14	HUGHES TAC #15	NORTHROP P530	JANAIR REQS †		VDS STUDY ††		AGREE
		REFERENCE STUDIES									
FLIGHT INFORMATION											
Attitude	- Pitch	X	X			X	M		P		✓
	- Roll	X	X			X	M		P		✓
	- Yaw	X									-
Pitch Trim		X				X	O		P		✓
Angle of Attack	- Actual		X			X			P		✓
	- Command						D				
	- Error										
Altitude	- Actual	X	X			X			P		✓
	- Command	X					M				-
	- Absolute (Radar)					X			P		✓
Vertical Velocity	- Actual	X				X	D		P		✓
	- Command										
Airspeed	- Actual	X	X			X			P		✓
	- Command	X					M				-
	- Mach Number	X				X			P		✓
*Time - Chronological						X			S		✓
Bank		X				X					-
Rate of Turn											
Sideslip											
Steering	- Command										
	- True Heading								P		-
	- Heading Command	X				X			P		✓
	- Heading Error						M				
	- Pitch Command										
	- Roll Command										
Velocity Vector	- Actual						O				-
Flightpath Deviation (Vertical)											
Flightpath Deviation (Lateral)											
Heading Relative to Runway											
Distance Along Runway											
Go Around (Waveoff) (Pull Up)											
NAVIGATION INFORMATION											
Heading		X				X	M		P		✓
Ground Track						X	M		S		✓
Course						X	M		P		✓
Ground Speed		X					D		P		✓
Aircraft Position	- Geo. Ref.	X				X	M		P		✓
	- Mission Ref.						M		P		✓
*Bearing to Objective						X			P		✓
Range to Objective						X	M		P		✓
Time to Objective							O		P		✓
Topographic Obstruction						X					-
Dangerous Weather (Loc. Ref.)							D				-
Fuel Quantity		X				X					-
Fuel Flow Rate		X				X			P		✓
*Fuel Range							D				-
Carrier or Base Position						X	O		P		✓
CONFIGURATION STATUS											
Landing Gear Position		X				X			P		✓
Speedbrake Position						X			P		✓
Trailing Edge Flap Position						X			P		✓
*Leading Edge Flap Position						X			P		✓
*Wing Sweep Position									P		-
Tail Hook Status / Drag Chute									P		-
SYSTEM STATUS											
Warning, Caution & Advisory		X				X			S		✓
PROPULSION SYSTEM											
RPM		X				X			P		✓
EGT		X				X			P		✓
EPR (Thrust)		X							P		✓
*Nozzle Position						X			P		✓
*Oil Pressure						X			P		✓
*Hydraulic Pressure						X			P		✓

† M = Mandatory
D = Desirable
O = Optional

†† P = Primary
S = Secondary

TABLE 4 ENROUTE PHASE - INFORMATION REQUIREMENTS COMPARISON MATRIX

IDENTIFIED INFORMATION REQUIREMENTS	DAC/ANIP	GRUMMAN ATT. A/C	HUGHES TAC #14	HUGHES TAC #15	NORTHROP P530	JANAIR RECS *		VDS STUDY **		AGREE
	REFERENCE STUDIES									
FLIGHT INFORMATION										
Attitude - Pitch	X	X			X	M		P		✓
- Roll	X	X			X	M		P		✓
- Yaw	X									-
Pitch Trim	X				X	D		S		✓
Angle of Attack - Actual										
- Command										
- Error										
Altitude - Actual	X	X			X			P		✓
- Command	X	X				M		P		✓
- Absolute (Radar)					X			P		✓
Vertical Velocity - Actual	X				X			S		✓
- Command						D				
Airspeed - Actual	X	X			X			P		✓
- Command	X	X				M				-
- Mach Number	X				X			S		✓
*Time - Chronological					X			S		✓
Bank	X									-
Rate of Turn					X	O				-
Sideslip					X	O				-
Steering - Command										
- True Heading								P		✓
- Heading Command	X					M		P		✓
- Heading Error										
- Pitch Command										
- Roll Command										
Velocity Vector - Actual						D				-
Flightpath Deviation (Vertical)										
Flightpath Deviation (Lateral)										
Heading Relative to Runway										
Distance Along Runway										
Go-around (Waveoff) (Pull Up)						O†		P†		-
NAVIGATION INFORMATION										
Heading	X				X	M		P		✓
Ground Track					X	M		S		✓
Course					X	M		P		✓
Ground Speed	X					D		P		✓
Aircraft Position - Geo. Ref.	X				X	M		P		✓
- Mission Ref.	X							S		✓
*Bearing to Objective					X			S		✓
Range to Objective	X				X	M		S		✓
Time to Objective	X					O		P		✓
Topographic Obstruction	X				X			S		✓
Dangerous Weather (Geo. Ref.)	X					D				-
Fuel Quantity	X	X			X			S		✓
Fuel Flow Rate	X	X			X			S		✓
*Fuel Range						D		P		✓
Carrier or Base Position					X	O				
CONFIGURATION STATUS										
Landing Gear Position										
Speedbrake Position										
Trailing Edge Flap Position										
*Leading Edge Flap Position										
*Wing Sweep Position										
Tail Hook Status / Drag Chute										
SYSTEM STATUS										
Warning, Caution & Advisory	X	X			X			S		✓
PROPULSION SYSTEM										
RPM	X				X			P		✓
EGT					X			P		✓
EPR (Thrust)	X							P		✓
*Nozzle Position					X			S		✓
*Oil Pressure					X			S		✓
*Hydraulic Pressure					X			S		✓

* M - Mandatory
D - Desirable
O - Optional
† - Low Altitude Only

** P = Primary
S = Secondary
† = Low Altitude Only

TABLE 5 LANDING PHASE - INFORMATION REQUIREMENTS COMPARISON MATRIX

IDENTIFIED INFORMATION REQUIREMENTS	DAC/ANIP	GRUMMAN ATT. A/C	HUGHES TAC #14	HUGHES TAC #15	NORTHROP P530	JANAIR RECS*		VDS STUDY††		AGREE
	REFERENCE STUDIES									
FLIGHT INFORMATION										
Attitude - Pitch	X	X	X	X	X	M		P		✓
- Roll	X	X	X	X	X	M		P		✓
- Yaw	X									-
Pitch Trim	X				X	D		P		✓
Angle of Attack - Actual		X		X	X			P		✓
- Command						M		P		✓
- Error										
Altitude - Actual	X	X	X	X	X			P		✓
- Command	X		X	X		M		P		✓
- Absolute (Radar)					X			P		✓
Vertical Velocity - Actual	X		X			D		P		✓
- Command										-
Airspeed - Actual	X	X	X	X	X			P		✓
- Command	X		X	X		M		P		✓
- Mach Number	X				X					-
*Time - Chronological					X					-
Bank	X				X					-
Rate of Turn			X		X	O		P		✓
Sideslip					X	O				-
Steering - Command				X						-
- True Heading								S		✓
- Heading Command	X		X	X		M		P		✓
- Heading Error								P		✓
- Pitch Command										
- Roll Command			X							
[illegible] - Actual						D		P		✓
[illegible] (Vertical)				X	X	M		P		✓
[illegible] (Lateral)					X			P		✓
[illegible]	X									-
[illegible]		X								-
[illegible]						[illegible], M, S		P		✓
NAVIGATION INFORMATION										
Heading	X		X	X	X	X		P		-
Ground Track			X		X	M				-
Course				X	X	M		P		✓
Ground Speed	X		X							-
Aircraft Position - Geo. Ref.	X		X	X	X	M		P		✓
- Mission Ref.	X					M		S		✓
*Bearing to Objective								P		-
Range to Objective	X	X				M		P		✓
Time to Objective	X					D				-
[illegible] Obstruction			X		X					-
[illegible] Weather [illegible]	X		X			D		S		✓
Fuel Quantity	X	X	X		X			S		✓
Fuel Flow Rate	X		X		X			S		✓
*Fuel Range						D		P		✓
Carrier or Base Position			X	X	X	O		P		✓
CONFIGURATION STATUS										
Landing Gear Position	X		X		X			P		✓
Speed Brake Position			X		X			P		✓
Trailing Edge Flap Position					X			P		✓
*Leading Edge Flap Position								P		-
*Wing Sweep Position								P		-
Tail Hook Status / Drag Chute	X							P		✓
SAFETY STATUS										
[illegible]	X	X			X			S		✓
PROPULSION SYSTEM										
RPM	X				X			P		✓
EGT	X				X			S		✓
EPR (Thrust)	X							P		✓
*Nozzle Position					X			S		-
*Oil Pressure					X			S		-
*Hydraulic Pressure					X			S		✓

* M - Mandatory   ** P - Primary
D - Desirable   S - Secondary
O - Optional

Table 5 presents the information items identified for the Landing Phase. The items identified in the VDS study column included all of the second level functions of the Recovery Phase (function 1.15) and second level functions 1.14.2, 1.14.5 and 1.14.6 of the Carrier Rendezvous phase. This arbitrary combination of mission phases was necessary for the comparison to several previous studies which included let-down, approach, and landing in the Landing Phase. Out of a total of 56 identified items, 38 of the VDS study items agreed with one or more of the referenced study items. There was disagreement in 18 items. Again, differences between the requirement for command vs actual information were evident. Five "difference" items pertained to navigation information and three to new items in the Configuration or Propulsion categories. Seven items in the Flight Information category were in disagreement. These were: yaw, Mach number, bank, sideslip, time, and two command items noted previously.

The authors of the JANAIR Report (ref. 1, page 32) noted that: ".... with few exceptions, there is little agreement about the items of information required for flight and navigation. All (their reference) studies agreed that attitude information (pitch and roll) is needed, but thereafter disagreements begin to emerge." It appears that the VDS study Information Requirements analysis does little to contradict their statement. However, as they point out, perusal of the individual VDS IR flight items (and combination of items) reveals most of "these disagreements are more apparent than real." Additionally, many of the differences found between "actual" vs "command" flight information and several of the navigation requirements can be attributed to some extent to the type of mission flown, the specifics created by the mission requirements, the mission scenario, plan, flight profile, etc. Another factor which probably will not be resolved in the near future is that apparently pilots either: "fly" a mission phase differently, or use different information to accomplish the same operation, or at least report that different information is required to accomplish the phase being considered. To some extent this apparent difference of opinion between what information is necessary and sufficient is also applicable to system operators in accomplishing navigation tasks.

In summary, there are identifiable differences in information requirements for the specific mission phases analyzed here. It is very probable that the majority of these differences are more apparent than real in the practical VDS control/display context. All identified differences appear to be resolvable within the context of the VDS design goals.

1.8 VSD INFORMATION CONTENT ANALYSIS

This section is a review of the information content of vertical situation displays in current operational aircraft. The aircraft reviewed included the A-6A, A-7D and the F-111A. These aircraft were selected because they currently fly missions and deliver weapons similar to those missions and weapons described in this study. The A-6 and A-7 are subsonic, but the actual velocity of the aircraft is not critical for determining the VDS content.

All of the displays of the identified aircraft which contain vertical situation information have been analyzed for content in this section. These include the Vertical Display Indicator (VDI) of the A-6, the Attitude Director Indicators (ADI) of the F-111A and the A-7, the Head up Display of the A-7, and the Lead Computing Optical Sight (LCOS) of the F-111. The rationale for combining the contents from these somewhat disparate displays in this analysis is simply stated: All content which is pertinent to aircraft control in the vertical plane must be considered for inclusion in the vertical displays of future aircraft. Thus, by considering all of the content that is now displayed, the resulting matrix of display content is comprehensive for current operational requirements. Future operational requirements, based on the projected missions, have been identified in Section 1.7, and will not be repeated in this section.

In reviewing the various pilot flight manuals (6,7,8) for display content, it is obvious that standardization of electronic displays symbology and nomenclature has not been accomplished. That this is a matter for concern is shown by the efforts of the Aircrew Station Standardization Panel to achieve consensus among the Services as to symbology and nomenclature for electronic and optically generated displays. This consensus, when achieved, will be reflected in revisions to MIL-D-81641. Until standardization has been accomplished, it may be anticipated that the symbols and their names used on electronically and optically generated displays will remain controversial and, indeed, may remain so even afterward. Failure to achieve standardization has proved costly in the past, and it is regrettable that its undesirable effects are now reappearing in the development of the present generation displays.

The consequences of failure to standardize are legion, but two in particular deserve mention. First, training men to recognize and effectively use new symbols and nomenclature for information content which already has

established referents in their minds is wasteful and inefficient. Secondly, and related to the first, is the real danger of negative transfer, which may lead to the use of a previously established response pattern which is inappropriate for the new situation, often with disastrous results. Northrop personnel working on this study are cognizant of these pitfalls in display design and have bent every effort to identify the most common symbology and nomenclature as a basis for development of the VDS display content.

Another problem, previously identified by the authors of the JANAIR study formerly cited (ref.2) and confirmed here, is the dearth of usable information for this analysis in several of the flight manuals. This deficiency is in the display content specific to the individual flight modes. The F-111A manual is particularly limited in information on the content of the LCOS display in the various attack modes. The A-7 manual, by comparison, offers an abundance of information on the symbology used on the HUD in various flight modes. The A-6 manual, while more informative than the F-111 manual, still leaves much to be desired, especially in the display content for the attack modes. Again, the analysis presented here is as complete and accurate as the original source material permits.

To facilitate the cross check of findings of the VDS content analysis with the results of earlier studies, the structure of the information content provided in the JANAIR study (ref. 2) has been utilized here. To this basic list was appended those additional information items which have been identified as present in one or more of the display modes of the representative aircraft. The F-14 aircraft is also included in the matrix. However, the information available on the F-14 displays was limited to the Design Control Specification for the Vertical Display Indicator Group (VDIG)[9]. This specification does not describe the various flight modes in which the individual information items are used. Nor does the specification identify that display symbology which is unique to the Phoenix weapon. Consequently, the F-14 information content is used here as confirmatory data. That is, if the F-14 displays appear to present information which has also been identified tentatively as necessary in the information requirements analysis, this tends to confirm its importance for future display applications. Other than this confirmatory role, the amount of information available on the F-14 VDIG has not been sufficient in and of itself to warrant using the F-14 information content as a basis for future display content recommendations.

Concerning the results of the analysis of current display content, the following should be noted. The pitch trim indicators, identified as present on the A-6A VDI for takeoff, enroute, and landing, have not been included as recommended display content for the future. The basis for this deletion was information received from an authoritative source[10] which indicates that pitch trim is no longer considered necessary by operational pilots.

For the Takeoff Phase (Table 6) 10 items of information have been identified as necessary in the original analyses of information requirements. The last column of Table 6 and the last column in the subsequent four tables reflect these information requirements analysis findings. Thus it is possible to compare what was found to be desirable information content through the mission and function analysis with what is currently displayed in operational systems. In the case of takeoff, it can be seen that the extent of agreement is substantial. Only one IR, velocity vector, which is present on both the A-6 VDI and the A-7 HUD, is not identified as necessary for takeoff on future vertical displays. For effective pitch control, which is critical for takeoff and especially carrier launch, it appears much more important to provide an accurate pitch attitude referent rather than velocity vector information. It has been learned that steps are being taken to add a pitch attitude referent to the A-7 HUD, probably in recognition of the limited value of the velocity vector for takeoff.

In the Enroute Phase (Table 7), five major items of flight information present on either the A-6 or A-7 displays have not been identified in the VDS IR analyses as necessary for future displays in this mode. These are angle of attack, turn rate, vertical velocity, velocity vector, and pull-up. The reader should reflect that for the purposes of this analysis Enroute is used to describe the (relatively) high altitude flight phase of the missions described here. These information items are not considered necessary for what is essentially straight and level cruise.

The Landing Phase (Table 8) shows essential agreement between the VDS IR analysis determined items and those found on one or more operational displays for this mode. The four exceptions are pull-up, range to go, flight path angle, and the landing director symbol. The pull-up signal is available on

TABLE 6 VERTICAL SITUATION DISPLAY INFORMATION CONTENT SUMMARY

TAKEOFF PHASE

INFORMATION DISPLAYED / AIRCRAFT	A-6A ADI	A-7 D/E HUD	A-7 ADI	F-111A ADI	F-111A LCOS	F-14 HUD	F-14 VDI	IDENTIFIED INFO REQMTS**
PITCH ANGLE	X		X	X		X	X	✓
PITCH TRIM	X							✓
ANGLE OF ATTACK	X	X						✓
ROLL ANGLE	X	X	X	X		X	X	✓
HEADING		X	X	X	X	X		✓
STEERING	X	X						✓
VERTICAL ORIENTATION*	X	X				X	X	✓
ALTITUDE		X				X	X	✓
VERTICAL VELOCITY		X				X		✓
AIRSPEED		X				X	X	✓
VELOCITY VECTOR	X	X						
FLIGHT PATH ANGLE (Pitch minus AOA)		X						

TABLE 7 VERTICAL SITUATION DISPLAY INFORMATION CONTENT SUMMARY

ENROUTE PHASE

INFORMATION DISPLAYED / AIRCRAFT	A-6 ADI	A-7 D/E HUD	A-7D ADI	F-111A ADI	F-111A LCOS	F-14 HUD	F-14 VDI	IDENTIFIED INFO REQMTS**
PITCH ANGLE	X		X	X		X	X	√
PITCH TRIM	X							√
ANGLE OF ATTACK	X	X						
ROLL ANGLE	X	X	X	X		X	X	√
HEADING		X	X			X	X	√
STEERING	X	X		X	X	X	X	√
VERTICAL ORIENTATION*	X	X				X	X	√
ALTITUDE	X	X				X	X	√
VERTICAL VELOCITY		X						
AIRSPEED		X				X	X	√
VELOCITY VECTOR	X	X						
PULL-UP	X	X						

TABLE 8 VERTICAL SITUATION DISPLAY INFORMATION CONTENT SUMMARY

LANDING PHASE

INFORMATION DISPLAYED / AIRCRAFT	A-6A ADI	A-7 D/E HUD	A-7D ADI	F-111A ADI	F-111A LCOS	F-14 HUD	F-14 VDI	IDENTIFIED INFO. REQMTS **
PITCH ANGLE	X		X			X	X	✓
PITCH TRIM	X							✓
ANGLE OF ATTACK	X	X				X	X	✓
ROLL ANGLE	X	X	X			X	X	✓
HEADING		X	X	X		X	X	✓
STEERING	X	X						✓
TURN RATE								
VERTICAL ORIENTATION*	X	X				X	X	✓
ALTITUDE		X				X	X	✓
VERTICAL VELOCITY		X				X		✓
AIRSPEED		X				X	X	✓
VELOCITY VECTOR	X	X				X		✓
PULL-UP	X					X		
GLIDESLOPE	X	X	X	X	X	X	X	✓
GLIDEPATH	X	X	X	X	X	X	X	✓
WAVEOFF		X				X	X	✓
RANGE TO GO								✓
FLIGHT PATH ANGLE (Pitch Minus AOA)		X						
LANDING DIRECTOR SYMBOL		X				X	X	

the A-6 VDI, but it has not been identified as necessary for future displays. The waveoff command appears to serve the same purpose as the pull-up command on landing, and duplication of commands is unnecessary for this mode. Range to go (to touchdown point) while not currently displayed, appears to be very desirable for the landing mode, especially where the pilot must execute a flare maneuver prior to touchdown. Under conditions of severely restricted forward visibility, the timely execution of the flare maneuver can be crucial for proper landing. The flight path angle and landing director content items found in current displays have not been identified as needed in the future VDS content. These items are derivatives of data which exist in other forms. Flight path angle is the derivative of pitch angle minus angle of attack. The landing director symbol gives pitch and roll steering commands, which are also presented on the more conventional glideslope and glidepath steering bars on other displays. It is felt that the more conventional method of presentation is justified for future applications.

Terrain Following (Table 9) appears to be the most controversial of the mission phases in terms of what is currently presented on displays vs what has been identified as needed for future displays. However, the data needed to complete this table are limited by the lack of information in flight handbooks concerning the information actually displayed in the various flight modes. It is entirely possible that many items of information identified as desirable in the JANAIR study actually do appear in the Terrain Following mode on certain of these displays. However, the limitations of the source material preclude absolute identification of such content. The IR analysis of future requirements only identified a limited number of items of information which appear to be necessary and sufficient to perform Terrain Following. It may be anticipated that as the quality of low-altitude sensors inproves, the complexity of the Terrain Following display modes will increase, giving the pilot more options in selecting his flight path. The result will be more information on the display. But what cannot be established with certainty at this time is precisely what this added information will involve.

Weapon Delivery (Table 10) shows reasonable agreement between current display content and the VDS information requirements. The velocity vector appears

TABLE 9 VERTICAL SITUATION DISPLAY INFORMATION CONTENT SUMMARY

TERRAIN FOLLOWING MODE

INFORMATION DISPLAYED \ AIRCRAFT	A-6A ADI	A-7 D/E HUD	A-7D ADI	F-111A ADI	F-111A LCOS	F-14 HUD	F-14 VDI	JANAIR REPORT RECOMMENDATIONS*	IDENTIFIED INFO REQMTS**
PITCH ANGLE		X				X	X		✓
PITCH TRIM									
ANGLE OF ATTACK									
ROLL ANGLE		X				X	X	X	✓
HEADING		X				X	X	X	✓
STEERING				X	X	X	X	X	✓
VERTICAL ORIENTATION*	X					X	X		✓
ALTITUDE	X	X				X	X	X	✓
VERTICAL VELOCITY		X				X			
AIRSPEED						X	X	X	✓
VELOCITY VECTOR		X				X			
PULL-UP		X		X	X	X			✓
GLIDESLOPE OR PITCH STEERING BAR			X	X	X	X	X		
GLIDEPATH OR BANK STEERING BAR			X	X	X	X	X		
FLIGHT DIRECTOR SYMBOL		X				X	X		
FLIGHT PATH ANGLE (Pitch minus AOA)								X	
TERRAIN CLEARANCE ANGLE	X							X	
TERRAIN RANGES	X							X	✓
AZIMUTH DISPLACEMENT (TURN)	X							X	
FLIGHT PATH (Heading & Elevation)								X	
THROTTLE COMMAND								X	
CLIMB (PITCH) COMMAND				X	X	X	X	X	
RADAR ALTITUDE CURTAIN	X								
OFFSET IMPACT BAR	X								

*JANAIR Report No. 680505
**Ref Table I

TABLE 10 VERTICAL SITUATION DISPLAY INFORMATION CONTENT SUMMARY

WEAPON DELIVERY (AIR-TO-GROUND)

INFORMATION DISPLAYED / AIRCRAFT	A-6A ADI	A-7 D/E HUD	A-7D ADI	F-111A ADI	F-111A LCOS	F-14 HUD	F-14 VDI	IDENTIFIED INFO REQMTS**
PITCH ANGLE	X					X	X	✓
ROLL ANGLE	X					X	X	✓
HEADING								✓
STEERING	X	X				X	X	✓
VERTICAL ORIENTATION*	X					X	X	✓
ALTITUDE						X	X	✓
AIRSPEED						X	X	✓
VELOCITY VECTOR	X	X				X		
PULL-UP	X	X				X		✓
GLIDESLOPE OR PITCH STEERING BAR				X	X			
GLIDESLOPE OR BANK STEERING BAR				X	X			
SIDESLIP (Early model)*		X*	X					
RANGE TO GO	X				X	X	X	✓
"G" ERROR				X	X			
AIMING SYMBOL (Aim Point)		X						✓
BOMBFALL LINE		X				X		
SOLUTION CUES	X	X				X		
PULL-UP ANTICIPATION CUE		X				X		✓
TARGET SYMBOL	X					X		✓
FLIGHT PATH ANGLE (Pitch minus AOA)		X						
"G" LOAD								✓

on current displays but is not seen as a firm requirement for air-to-ground weapon delivery. Again, the IR's identified for the future attack aircraft appear to represent the necessary sufficient minimum data required for head down weapon delivery. And, just as in Terrain Following, it is reasonable to expect that as the effectiveness of weapon delivery computations increases, the complexity of the display will increase. Thus, a VDS which contains all of the information now planned for the F-14 VDIG may eventually be needed to deliver all of the weapons, in all of the modes, available to a circa 1985 tactical attack aircraft.

1.9 VDS ALLOCATION, CONTENT, AND FORMATING

This section contains the data derived from study tasks e, g, and h as outlined in section 1.1 and completes the Requirements Analysis conducted by Northrop Human Factors/System Analysis personnel.

The hypothetical panel layouts and the ground rules for allocation of the pilot's and System Operator's information requirements to various functional display areas are discussed in section 1.9.1. The VDS display contents for each mission phase are tabulated with an accompanying discussion in the following section. The final product of the Requirements Analysis, the VDS formats for selected critical mission phases, are shown and described in section 1.9.3. Although air-to-air weapon delivery is a critical mode for the VDS, no format has been designed for this mission phase. This was due to the unavailability of "Weapons Peculiar" and "Delivery Mode Parameter" information requirements, due to security or other classification problems associated with the use of this type data.

A preliminary design layout of a control panel for the integrated primary cockpit display groups conceptualized in section 1.9.1 is beyond the scope of this study. However, the F-14 VDIG Display control panel concept provides an excellent baseline for the design of the VDS control panel. As in the F-14 control panel, the pilot and S.O. must be able to select any of the primary VDS navigation or attack mode formats. Within each mode the operator must also have the option of selecting submode routines which are associated with the specific mode selected. Additionally, a single sensor or combination of sensors must be selectable as inputs to either (or both) displays.

The option to "declutter" the mode selected, and/or to expand the IR, radar, or TV sensor picture to the full 9.4-inch-square display area must be available to the pilot and system operator. As in the noted aircraft, a matrix switch pattern layout is recommended for the future control panel.

1.9.1 Information Allocation

To determine the information content of the integrated VDS, as specified in section 1.1(e), it was first necessary to allocate the total array of information items to various displays which will presumably be existent in

cockpits of the future. In this effort it was assumed that a cockpit concept similar to the Navy's Advanced Integrated Modular Instrumentation System (AIMIS) has been successfully implemented for the 1985 attack aircraft postulated herein. As a reference document for conceptualizing this cockpit of the future, the Boeing study[11], Integrated Information Presentation and Control Systems, was utilized. Figure 5, below, presents a cockpit concept which includes the integrated VDS and other electronically generated displays for the pilot. It is assumed that the conventional flight instruments present in the cockpit will primarily provide a backup function for the electronic displays.

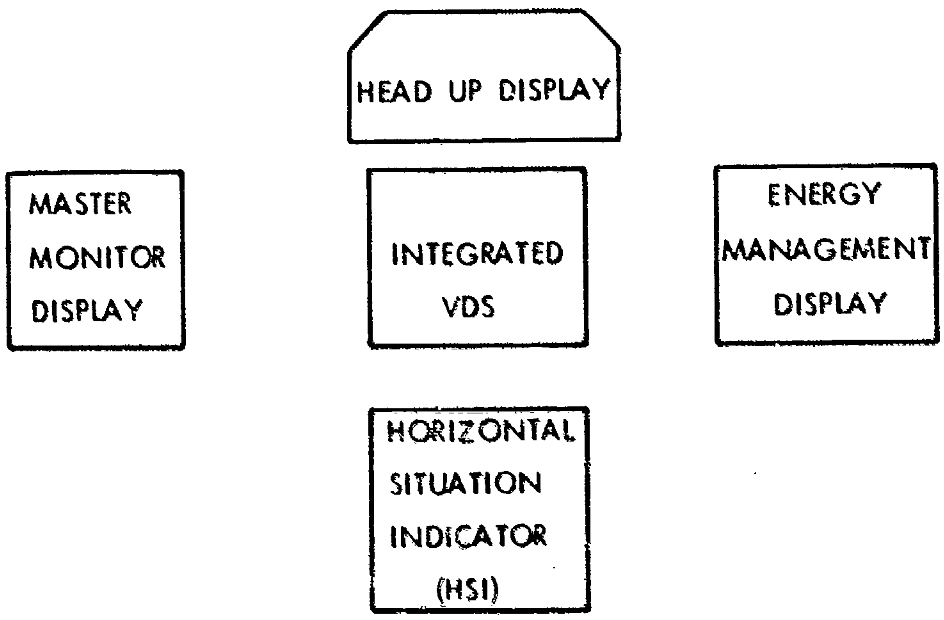


FIGURE 5 PILOT'S INSTRUMENT PANEL

The current configuration of the F-14A front cockpit represents a significant step toward the realization of this concept. The F-14 has a HUD, a

Vertical Situation Display (the VDI), and an HSI. Furthermore, the VDI is a true multimode display, with the pilot being given the option of selecting any type of sensor data available on the aircraft which is compatible with the display. The HSI also provides the option of viewing the electronically generated symbology present on the System Operator's combat situation display, alphanumeric information from data link, or Radar Homing And Warning data.

For the purposes of this analysis, only those items of required information which can logically be presented on the VDS have been so allocated; that is, primarily information which pertains to the aircraft flight path in the vertical plane appears on the pilot's VDS. The information content which does not apply to flight path control in the vertical plane is assumed to be available to the pilot on the other displays as follows:

a. All vehicle status, advisory, trend and caution information will be presented on the Master Monitor display. Primary responsibility for alerting the pilot and S.O. to warning and caution information will be allocated to the Voice Warning System (VWS).

b. All propulsion system data, energy management parameters, and fuel management information will be presented on the Energy Management display.

c. All information pertaining to flight control in the horizontal plane (except airspeed, which is presented on the VDS) will be presented on the HSI. This will be primarily navigation information; both ground mapping radar and projected map displays are available at the pilot's option. However, the center of the display area may also be used for other purposes, including monitoring of the S.O.'s displays, threat information, or data link commands, similar to the capability provided by the present F-14 HSI display.

d. The Head Up display will provide information on content comparable to that presented on the VDS. For the purposes of this analysis, it is assumed that all information identified as necessary for flight operations by reference to the VDS in the "head down" mode

will also be selectively available to the pilot on his HUD when he is flying the aircraft "head up."

The System Operator's functional panel layout for the hypothesized attack aircraft is shown in Figure 6 below.

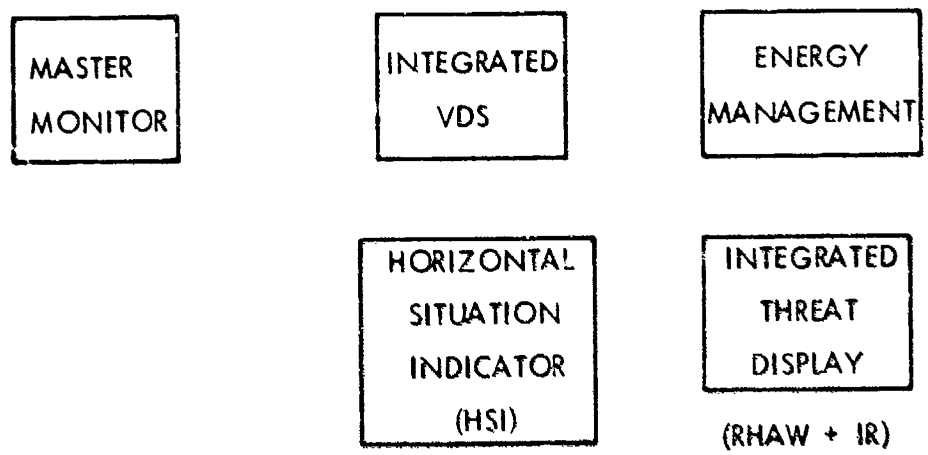


FIGURE 6 SYSTEM OPERATOR'S INSTRUMENT PANEL

Again, the information content determined to be appropriate for the S.O.'s VDS has been so allocated, and the remainder of the information has been allocated to the other displays. The primary difference in the S.O.'s and pilot's stations is the addition of a separate threat display in the S.O.'s panel and the deletion of the HUD, which is incorporated in the pilot's panel. HUD data is, of course, not relevant to the rear seat occupant in this tandem aircraft concept. The addition of a separate threat display on the S.O.'s panel reflects the increasing importance and complexity of the threat environment, and the allocation of threat counteraction as a primary S.O. function in the missions described here.

As in the case of the pilot's panel, the information allocation to the various displays reflects the desirable goal of functional grouping to simplify the System Operator's perceptual load.

The information requirements allocated to the S.O.'s VDS reflect the functions he will perform in the missions described here. It is logical to assume that he will use his VDS to accomplish the major tasks of target detection, standoff missile control, and aircraft identification (IFF) utilizing TISEO and other sensors. Hence the S.O. will be using his VDS more extensively in the TV mode than will the pilot. However, it is assumed that the S.O. will also use FLR and FLIR sensors as the situation demands, by selection of the appropriate mode for his own display. Thus he will be able to assist the pilot in such critical mission phases as air-to-air refueling, carrier approach and recovery.

1.9.2 VDS Content

Tables 11, 12, and 13, following Section 1.9.2, shows the allocation of information content to the pilot's and the system operator's VDS for both missions described in Sections 1.4 and 1.6. Each table is a matrix in which the column headings are the phases which appear in that particular mission, while the rows of the matrix are the information items which have been identified for inclusion in the VDS. Whenever an X appears in an individual column, it indicates that a particular item of information has been deemed necessary for presentation on the VDS for that particular mission phase.

The information content of the pilot's VDS required for the seven mission phases contained in Mission No. 1 is shown in Table 11. By inspection, it can be seen that the phases of Launch and Climbout and Enroute Cruise are virtually identical, differing only in the requirement for a dangerous weather symbol on the display in the enroute mode. For purposes of efficiency, these two phases have been combined in the description of the recommended VDS format shown in Section 1.9.3.

By inspection of the remaining phases of Mission No. 1, it can be seen that there is a "core" of information requirements which apply to all phases. These core requirements pertain to vehicle attitude, altitude, and velocity control. To this core of flight control information requirements is added those items necessary to perform the unique aspects of each mission phase. In Recovery and Landing, the requirements for precision flight path control with reference to a (relatively) fixed landing point dictate the need for information

on heading and glideslope error and on the actual velocity vector of the aircraft, and for "waveoff command" if required. Also, command angle of attack information will assist the pilot in making a precision approach to touchdown.

Terrain Following mode requires precision vertical flight path commands to enable the pilot to clear the terrain, in addition to the information required for attitude and velocity control. In Terrain Avoidance mode, more information is required on the display to permit the pilot to choose his best path around obstacles and dangerous weather.

In the attack mission phases, both air-to-ground and air-to-air, the pilot needs additional information to locate and identify the target, and to control his flight path and velocity precisely during the terminal guidance phase of his weapon delivery run, without exceeding the "g" limits of his aircraft.

Mission No. 2 VDS information contents are summarized in Table 12, again illustrating the general requirements for attitude, altitude, and velocity control across all mission phases. Added to these generalized requirements are such mission phase peculiar requirements as: stationkeeping during the Cruise phases, air refueling in the Carrier Rendezvous phase, and the requirements peculiar to remote control of a standoff missile in the Standoff Weapon Attack phase.

Table 13 summarizes the VDS requirements for the System Operator's station. In Mission No. 1, the S.O. needs information which will facilitate target detection, identification, and designation. In Mission No. 2, the list of information requirements for standoff weapon control is considerably expanded, reflecting the severe demands of remote vehicle control. In the SAM Attack phase, there is reflected the need for specific threat detection information. In all of the mission phases there are many S.O. information requirements that are conventionally and appropriately assigned to the other specialized displays available in his crew station. The conventional approach is continued in this study.

TABLE 11 ALLOCATED VDS CONTENT MISSION NO. 1

PILOT'S STATION

MISSION PHASE		Launch & Climbout	Enroute Cruise	Recovery (Landing)	Terrain Following	Terrain Avoidance	Weapon Del. Air-to-Gnd.	Air-to-Air Attack
Attitude	- Pitch	X	X	X	X	X	X	X
	- Roll	X	X	X	X	X	X	X
"G" Load							X	X
Angle of Attack	- Actual	X		X				X
	- Command			X				
Altitude	- Actual	X	X	X	X	X	X	X
	- Command		X	X	X	X		X
Vertical Velocity	- Actual	X		X				
Airspeed	- Actual	X	X	X	X	X	X	X
	- Command			X			X	
	- Mach Number	X	X		X	X	X	X
Rate of Turn				X				
Steering	- True Heading	X	X	X	X	X	X	
	- Heading Command	X	X	X	X		X	X
	- Heading Error			X				X
	- Pitch Command						X	
	- Roll Command						X	
Velocity Vector	- Actual			X			X	
Flightpath Deviation (Vertical)				X				
Flightpath Deviation (Lateral)				X				
Waveoff	- Command			X				
Pullup	- Command				X	X	X	
Terrain Avoidance	- Flt. Parameters					X		
Terrain Following	- Flt. Parameters				X			
Station Keeping								
Range to Objective							X	X
Time to Objective							X	X
Topographic Obstruction						X		
Dangerous Weather (Loc. Ref.)			X			X		
Target Identification							X	X
Designation	- (Aiming Point)						X	X
Threat Detection	- Type (Air or Gnd)						X	
	- Dir. & Range							X
Aircraft Identification								X
Delivery Mode Parameters							X	X
Weapon Peculiar Parameters								X

TABLE 12 ALLOCATED VDS CONTENT MISSION NO. 2

PILOT'S STATION

MISSION PHASE		Launch & Climbout	Enroute Cruise	Recovery (Landing)	Terrain Following	Terrain Avoidance	Stand Off Weapon Att.	SAM Attack	Air Refueling
Attitude	- Pitch	X	X	X	X	X	X	X	X
	- Roll	X	X	X	X	X	X	X	X
"G" Load								X	
Angle of Attack	- Actual	X		X					
	- Command			X					
Altitude	- Actual	X	X	X	X	X	X	X	X
	- Command		X	X	X	X	X		X
Vertical Velocity	- Actual	X		X					
Airspeed	- Actual	X	X	X	X	X	X	X	X
	- Command			X			X		X
	- Mach Number	X	X		X	X	X	X	
Rate of Turn				X			X		
Steering	- True Heading	X	X	X	X	X	X		X
	- Heading Command	X	X	X	X		X		
	- Heading Error			X					X
	- Pitch Command							X	X
	- Roll Command							X	X
Velocity Vector	- Actual			X					
Flightpath Deviation (Vertical)				X					
Flightpath Deviation (Lateral)				X					
Waveoff	- Command			X					
Pullup	- Command				X	X		X	
Terrain Avoidance	- Flt. Parameters					X			
Terrain Following	- Flt. Parameters				X				
Station Keeping (Refueling Parameters)*			X		X	X			(X)*
Range and Bearing (to Missile)*								(X)*	X
Time (to Missile)*							X	(X)*	
Topographic Obstruction						X			
Dangerous Weather (Loc. Ref.)			X			X			
Target Identification									
Designation - (Aiming Point)									
Threat Detection	- Type (Air or Gnd)								
	- Dir. & Range								
Aircraft Identification									X
Delivery Mode Parameters							X		
Weapon Peculiar Parameters									

TABLE 13 ALLOCATED VDS CONTENT SYSTEM OPERATOR'S STATION

MISSION PHASE		MISSION NO. 1			MISSION NO. 2		
		Weapon Del. Air-to-Gnd.	Air-to-Air Attack		Stand Off Weapon Att.	SAM Attack	Air Refueling
Attitude	- SWS Pitch				X		
	- SWS Yaw				X		
Altitude	- Actual				X		
	- Command				X		
Steering	- Heading Command				X		
	- Heading Error				X		
	- Pitch Command				X		
	- Yaw Command				X		
Bearing to Objective		X	X				X
Range to Objective		X	X		X	X	X
Time to Launch, C.P. or Tgt.		X	X		X		X
Topographic Obstruction		X			X		
Target Identification		X			X		
Designation - (Aiming Point)		X	X		X		
Threat Detection	- Type (Air or Gnd)					X	
	- Dir. & Range					X	
Aircraft Identification			X				X
Weapon	- Arm/Safe				X		
	- Select/Status						
Delivery Mode Parameters					X		
Weapon Peculiar Parameters		X	X		X		
SWS Thrust					X		
Auto/Manual Control					X		
Field of View					X		
Depression Angle					X		
Signal Strength					X		

1.9.3 VDS Formats

The formats for the recommended VDS display content for the mission phases previously identified are presented in this section. These formats represent a synthesis of the symbology and presentation techniques used in existing VDS-type displays, with some unique approaches to the display of the required information. In all instances, whether by selection of symbology or in the format design, the goal has been to implement the most effective display in terms of maximum legibility and interpretability by the pilot or system operator.

As has been previously noted, there is a woeful lack of standardization of symbology for electronic and optically generated displays. This lack of standardization of symbology dictated that Northrop choose the "best" symbols that exist on displays today, including Head-Up displays, and further, to improvise where necessary to meet future requirements. Assuming the tri-service standard for HUD symbology is coordinated and released in the near future, there will exist a uniform array of symbols which may also be used for VDS displays.

The size of the proposed VDS is 9.4 x 9.4 inches square. The approximate area of 81 square inches is actually more space than is necessary to display the required data for some of the mission phases. Therefore it is possible to use the edges of this display area for presenting parametric or trend flight information in an optimum format, with a desirable dark surround to produce high contrast and improved legibility. This parametric/trend information includes such data as airspeed, heading, altitude, angle of attack, and time to go. And since the display is entirely electronic, when a larger display area is desired, as in a multimode air-to-ground weapon delivery, the entire 81 square inches of the display is available for presenting wide angle target area coverage. This demonstrates the versatility of the all-electronic display.

The principal display modes of operation for the VDS are as follows with recommended formats for selected mission phases discussed in section 1.9.3.

VDS Modes for Pilot Station

- Launch/Climbout and Enroute (Cruise)
- Recovery (Approach and Landing)
- Terrain Following
- Terrain Avoidance
- Ground Mapping
- Weapon Delivery - Air-to-Ground
- Weapon Delivery - Air-to-Air
- Stationkeeping

The System Operator can select any of the display modes for the pilot's station and requires the following modes in addition. The recommended formats for the System Operator's station are discussed in sections 1.9.3.7 and 1.9.3.8.

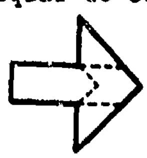
VDS Modes for System Operator Station

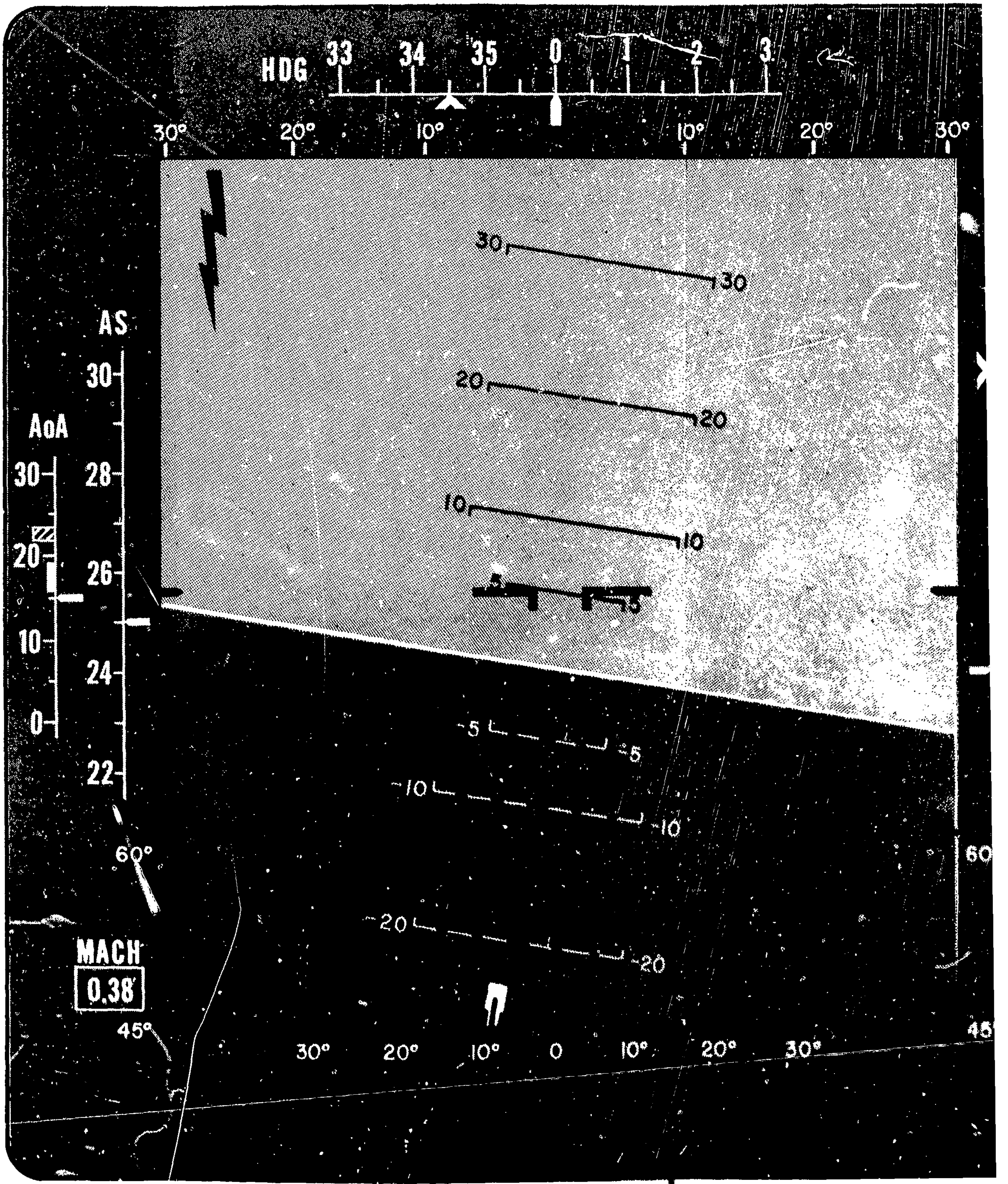
- Standoff Weapon Attack - Midcourse Mode
- Standoff Weapon - Terminal Guidance Mode

1.9.3.1 Launch/Climbout and Enroute (Cruise) Mode

Figure 7 depicts the pilot's VDS during the climbout maneuver shortly after launch from the aircraft carrier. As shown, the pilot is performing a 10° bank during a 5° climb. The VDS displays the actual (1200 ft) and command (1800 ft) altitude on the right hand side. The actual (250 knots) airspeed is displayed on the vertical scale on the left hand side. Angle of Attack is displayed adjacent to the airspeed scale and reads 15 units. Vertical Velocity is displayed adjacent to the altitude scale and shows a rate of climb in excess of 1,000 feet per minute. The actual (360°) and command (345°) heading scales are shown at the top of the display. The (10°) roll angle information is presented along the bottom of the VDS. Pitch (bars) are indicated as black solid lines above the horizon, while negative pitch bars are shown as broken white lines. The pitch ladder may contain bars at 5° intervals or 10° intervals to provide the pilot more (or less) precise pitch reference as required for specific modes. Dangerous weather (lightning symbol) is shown occurring approximately 27° to the left of his present course.

The "command" index is an open V-shape, while the "actual" index is a pointed bar. When actual is equal to command information these indices combine to form an arrow, thus:





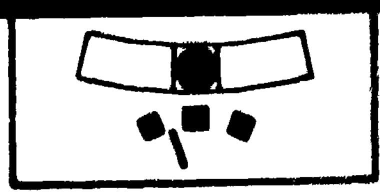
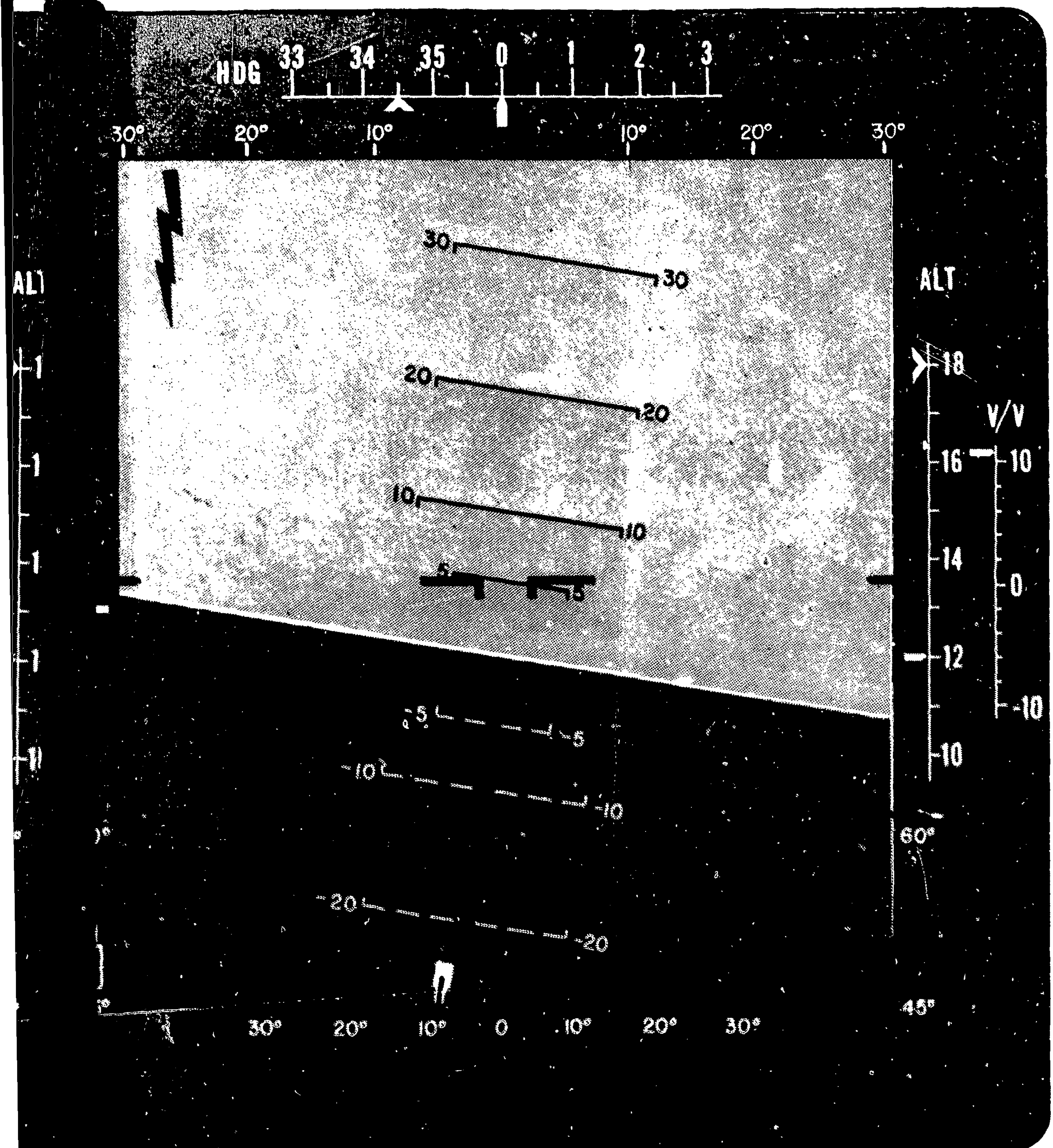


FIGURE 7 TAKEOFF AND CR



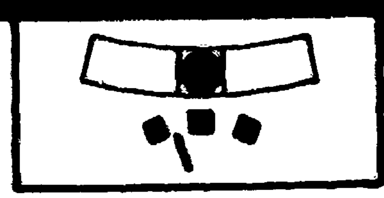


FIGURE 7 TAKEOFF AND CRUISE MODE

The basic VDS symbols used for the Launch/Climbout and Enroute Cruise phases are also contained in the remaining phases as applicable.

The scale labels included in this drawing are:

Airspeed	AS
Angle of Attack	AoA
Altitude	ALT
Vertical Velocity	V/V
Heading	HDG

1.9.3.2 Recovery (Approach and Landing) Mode

Figure 8 depicts the VDS format for a carrier approach and recovery. In addition to the normal horizon and aircraft reticle, certain other symbols have been modified or added to reflect the requirement for precision flight path control. An angle of attack indicator similar to the one used in the HUD symbology was added at the request of representatives of NADC. This indicator informs the pilot if his angle of attack is above or below a desired value. For exact absolute values the pilot can refer to the AoA indicator scale on the left of the display. The pitch ladder has been expanded with the addition of pitch lines at each 5°, to improve the pilot's pitch reference. The Precision Course Vector Symbol (PCVS) gives the pilot azimuth and elevation steering commands, as in the normal ILS. A velocity vector has been added to assist the pilot in predicting his touchdown point. All of the symbology is shown projected over a simulated view, or analog, of the real world. On the periphery of the display is presented both command and actual angle of attack, airspeed, and (radar) altitude. Radar altitude is indicated by a boxed R just above the altitude scale. Radar altitude is displayed up to 1000 feet and barometric altitude from 1000 to 99,000 feet. In this figure the absolute (radar) altitude is 300 feet and the commanded altitude is 380 feet. Actual vertical velocity is also presented. The heading scale has been expanded to provide more precise azimuth steering information to the pilot. Also included on the display is a digital readout of actual Mach, although this information is considered as secondary information during the approach, but useful where avoidance of the transsonic range is required. To the right of the PCVS symbol, the carrier deck (or runway) symbol is shown. The centerline of the carrier deck and the arresting cables (aiming point(s)) are indicated by crosses. A wave-off command (pull up symbol shown in Terrain Avoidance Mode) is projected when the approach does not meet the required flight path/air speed parameters.

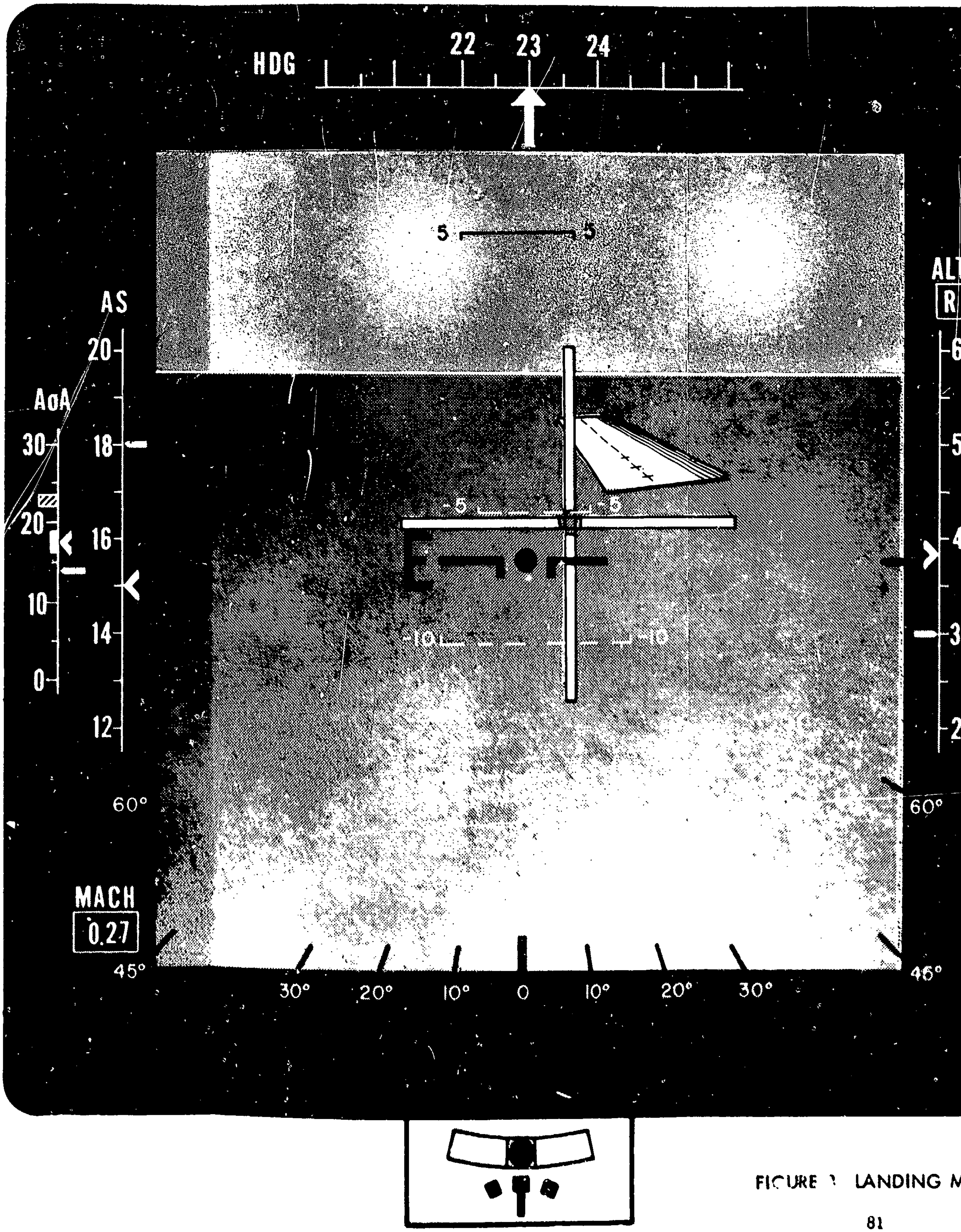


FIGURE ? LANDING M

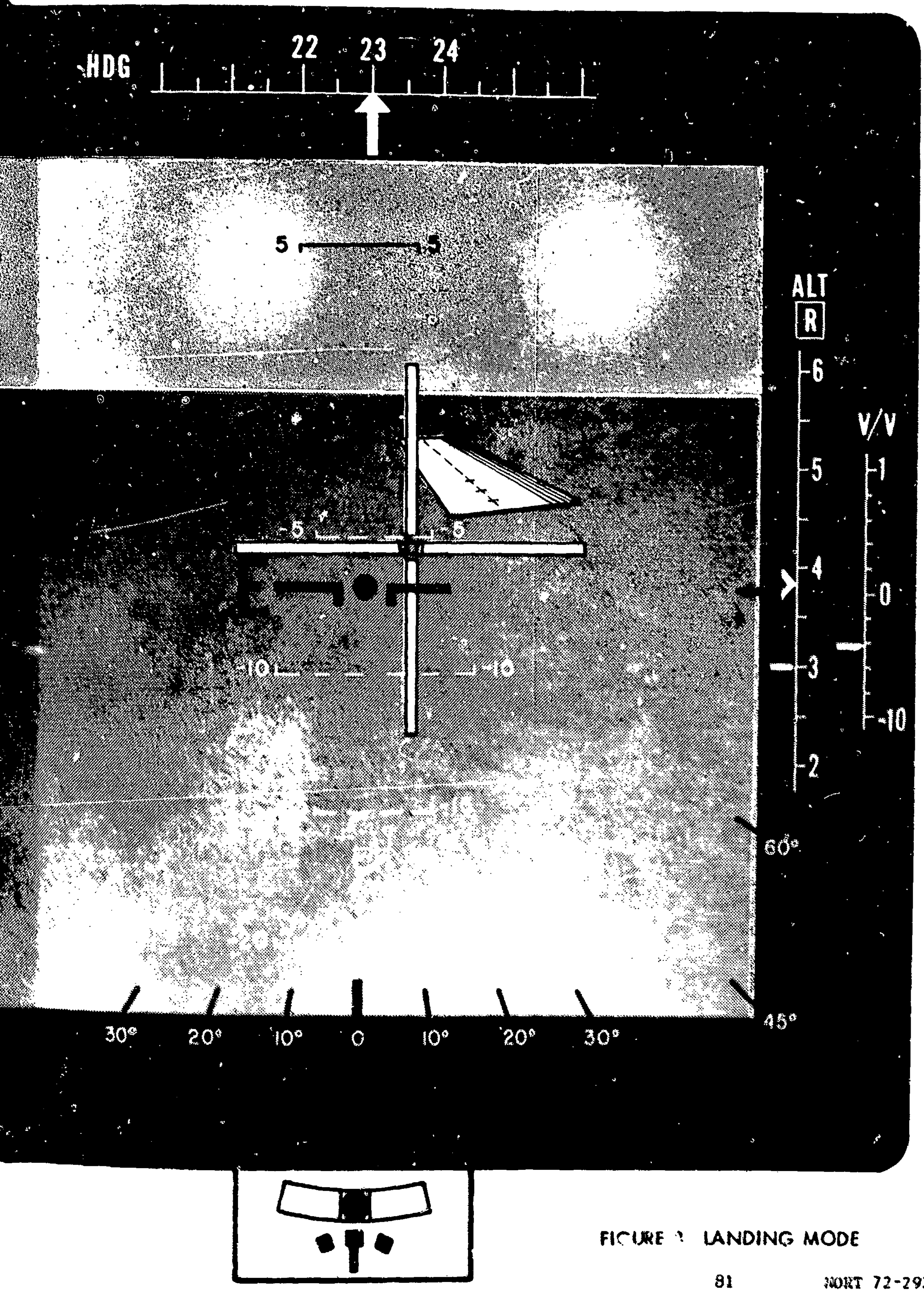


FIGURE [illegible] LANDING MODE

1.9.3.3 Terrain Following Mode

Figure 9 depicts the Terrain Following mode. This E-scan type display contains symbols representing both present and predicted position with respect to the terrain. Two symbols originate at the same point on the left edge of the display. The origin point (depicted by circle) of the vectors indicates the present position as relative to the terrain directly below the aircraft. The dashed line represents the aircraft velocity vector, indicating the point of impact upon the terrain if the flight path does not change. The arrow, the pitch vector predictor, rotates about its point of origin to indicate the effect of the pilot's control actions upon the aircraft. The tip of the arrow predicts the position of the aircraft after six seconds of flight. The point of origin of both symbols moves against a scale which gives the pilot a readout of his absolute altitude above the terrain.

Also added to the E-scan display is the aircraft reticle, horizon line, roll markers and pitch indices, presented in the normal VDS display mode. Heading, actual airspeed, Mach, and both actual and (upper and lower) command altitude are displayed to the pilot in this mode. The Pull Up Symbol, shown in the Terrain Avoidance mode is presented when impact warning is required.

1.9.3.4 Terrain Avoidance Mode

The VDS display presentation for the Terrain Avoidance Mode is shown in Figure 10. Terrain Avoidance differs from Terrain Following primarily in the pilot's freedom of choice to maintain his present ground track, or to make course changes to maximize the tactical advantages of terrain masking. That is, by selecting an optimum flight path, down valleys and around terrain obstacles, the pilot minimizes the enemy's ability to detect and track his aircraft by electronic or visual means.

This mode presents the terrain elevation and range in a series of shaded and coded bands. Specific ranges and coding options are in concurrence with the present ADI display, as specified in the A-6 Flight Manual (reference 5). The total range displayed (darkest terrain) is eight miles. The heavily banded area indicates 1/4 to 1/2 mile range, while the narrow banded area is 3/4 to 1 mile ahead of the aircraft's present position. AoA, AS, HDG, radar ALT, V/V,

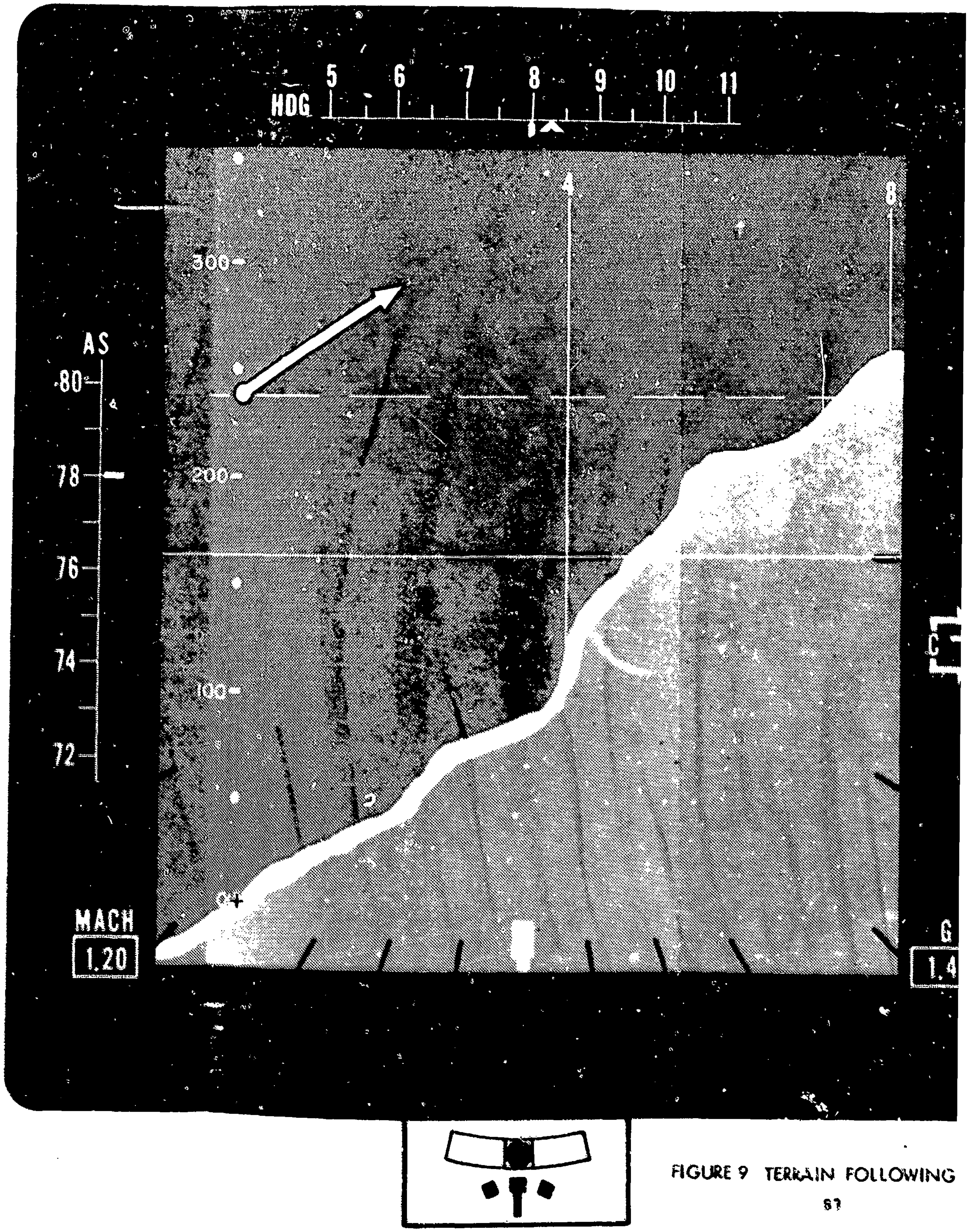


FIGURE 9 TERRAIN FOLLOWING

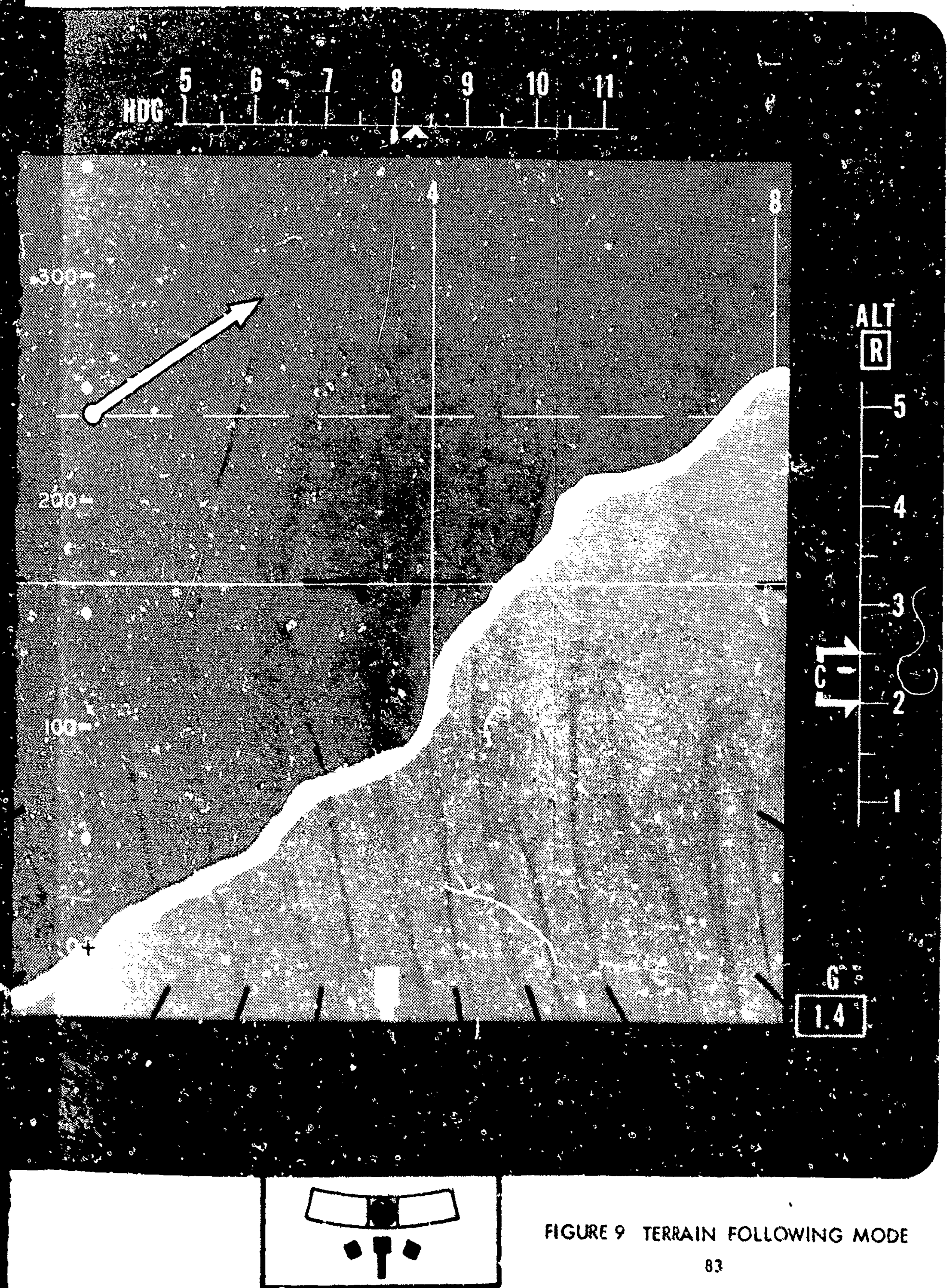


FIGURE 9 TERRAIN FOLLOWING MODE

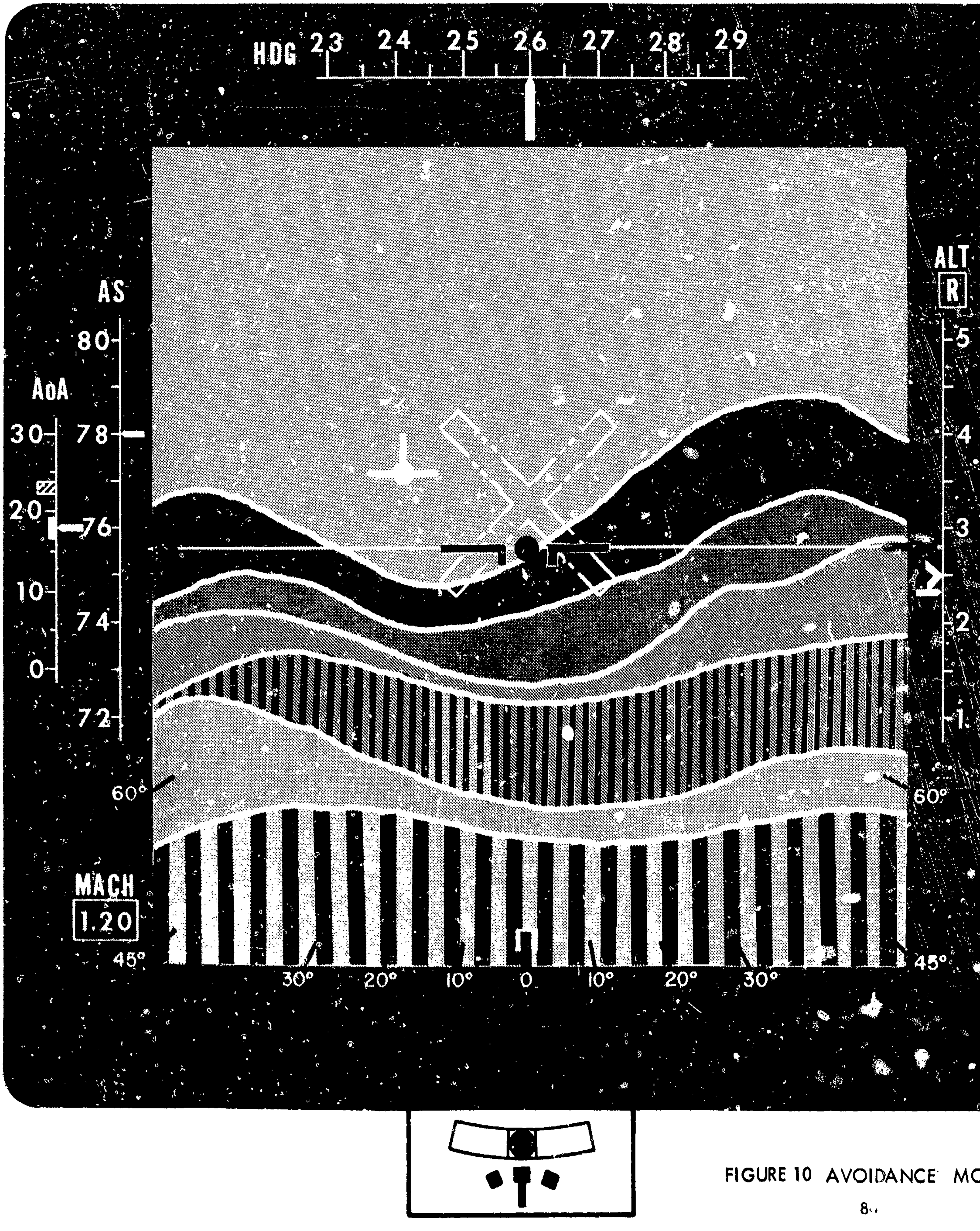


FIGURE 10 AVOIDANCE MO

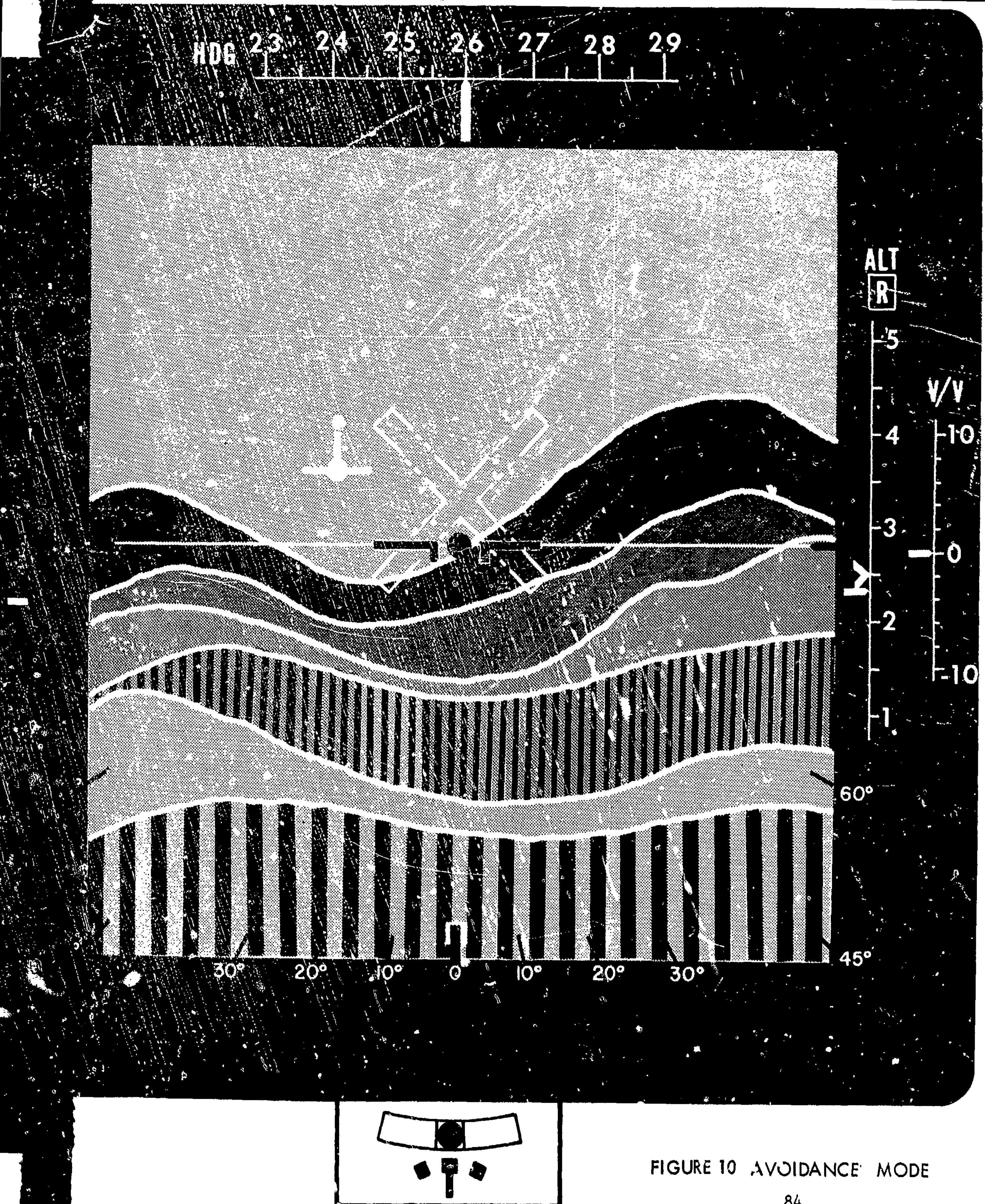


FIGURE 10 AVOIDANCE MODE

Mach and Roll information is presented in the peripheral (surround) area. Roll, Climb and Bank information is shown in the same manner as the previously described modes. A split Altitude Command Symbol, indicating both upper and lower altitude limits, as shown in Figure 9, could also be employed for this mode if future operational requirements necessitate.

The velocity vector is presented as a black circle, shown in this figure as centered in the Aircraft Reticle. Above and to the left of the reticle is the white Flight Director Symbol, showing a "fly to" command, e.g., climb and turn to the left. The Pull Up (Breakaway or Wave Off) command "X" is the symbol shown by dashed phantom lines. The Pull Up command would be displayed as a solid X, which blinks on and off at an optimum human alerting and detection rate, with the on/off rate increasing as the condition becomes more critical. It would appear as the brightest symbol on the display in this, or any of the other applicable modes. This symbol may appear in the Landing, Terrain Following, Terrain Avoidance, Weapon Delivery (air-to-ground) and in the Stationkeeping modes to denote critical "pull up" or "wave off" commands.

The Dangerous Weather Symbol would also appear in the Terrain Avoidance Mode if inclement weather conditions exist within 30^{o} left or right of the present flight path.

1.9.3.5 Weapon Delivery Mode

Figure 11 presents a typical air-to-ground bomb attack where the pilot has selected the radar sensor for the target acquisition display on the VDS. The actual radar return utilized for this figure shows relatively rough terrain in the foreground and a small airfield near the top of the picture. This figure represents a point in Mission No. 1 profile shortly after the aircraft pop up maneuver has been executed. In the total system concept hypothesized, the pilot or the S.O. (perhaps using a different combination of sensors on his VDS) identifies the target and positions the diamond-shaped Target Designate Symbol (TDS) on the target aiming point. Upon receipt of the designation signal, the computer solves the range and deviation from present aircraft heading. The computed command heading (84^{o}) is displayed along with the actual heading (90^{o}) as in the previous modes. Additionally, heading error is displayed as a 6^{o} angular deviation

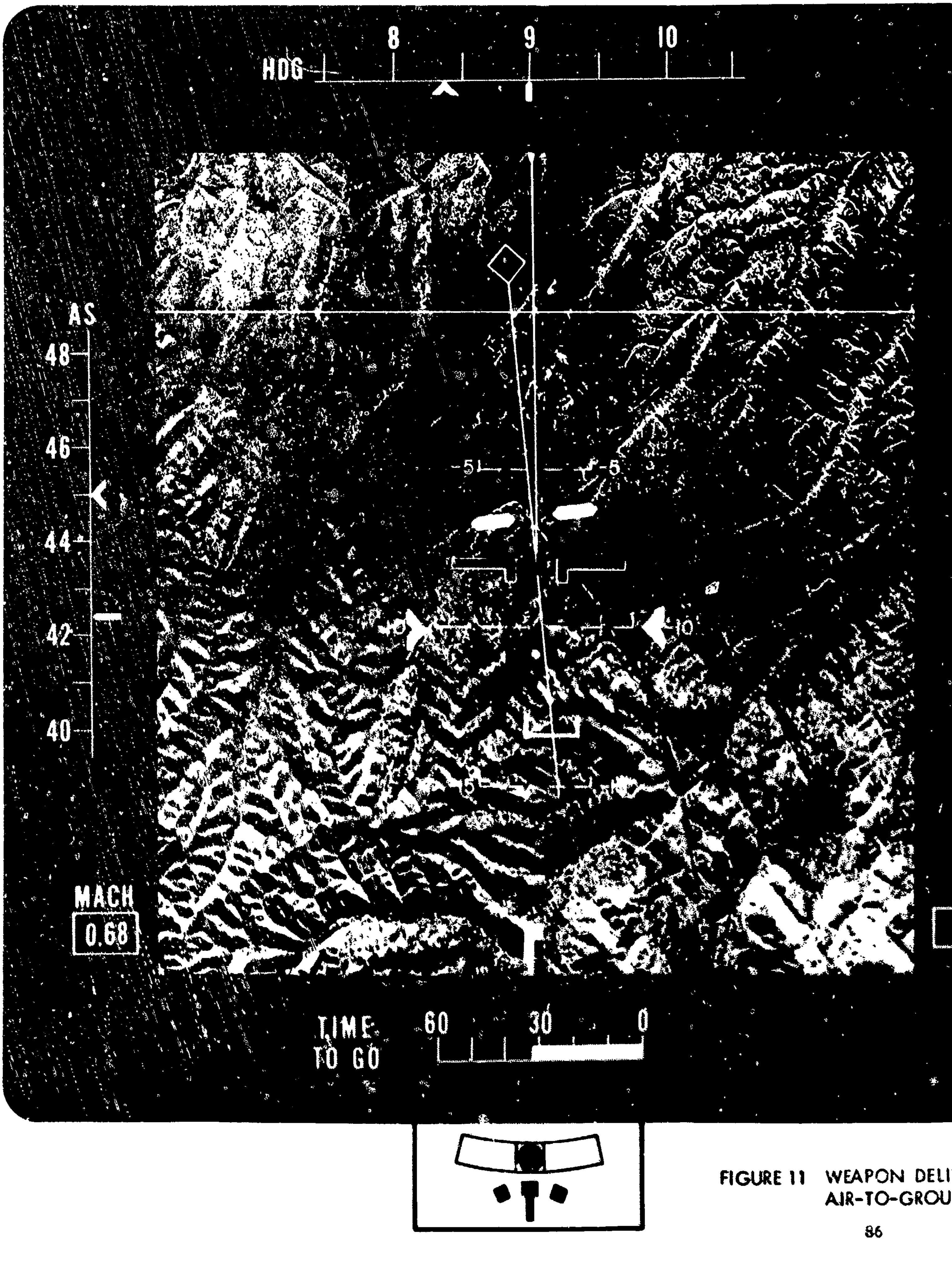


FIGURE 11 WEAPON DELI
AIR-TO-GROU

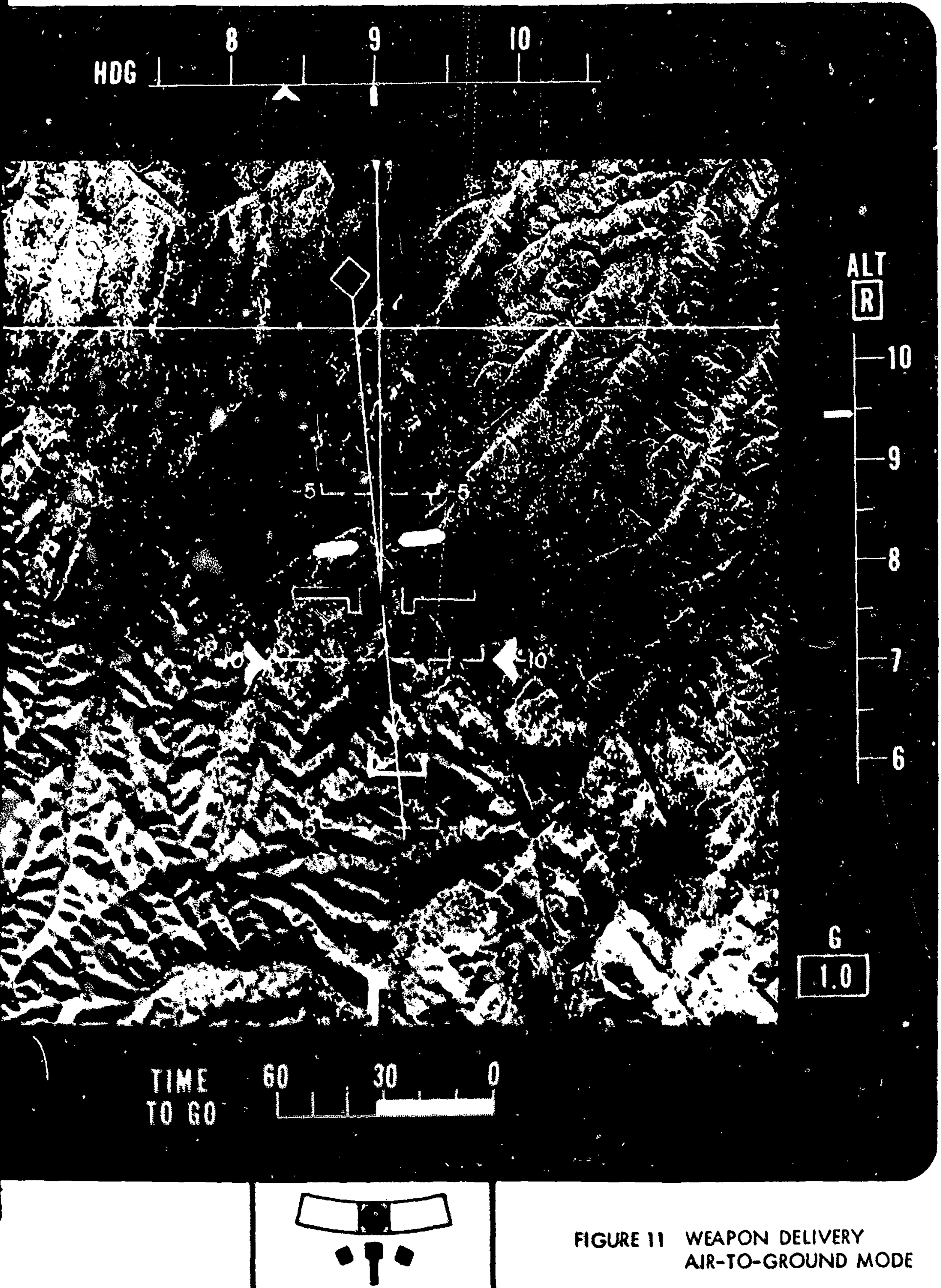


FIGURE 11 WEAPON DELIVERY
AIR-TO-GROUND MODE

between the white Command Track Line (CTL) which originates at the bottom of the TDS and runs through the Velocity Vector/Aircraft Reticle symbols, and the Present Track Line. Note: the CTL is sometimes referred to as the "Bomb fall line," or the "Bomb steering line" in HUD terminology. The aircraft's present track is indicated by the white Present Track Line (PTL), which is on the vertical centerline of the VDS and is similar to the HUD term "Local vertical." The Bomb Release Line Symbol (BRLS) consists of white, double pointed bars and is just above the aircraft reticle in the figure. The Pull Up Anticipation Cue Symbol is the white U-shaped symbol just above the -5° pitch line. The large Pull Up Command "X" would be displayed in this mode when appropriate.

The aircraft is presently pitched down approximately -8° with a 10° dive commanded, as shown by the Command "Vs" on either side of the -10° pitch lines. As the pilot initiates the 6° left turn commanded, the CTL, TDS and ground map will move to the right. As the pilot completes the turn, the Target Designator Symbol will lie on the PTL. As the aircraft moves nearer the target the radar "picture" will move down the display. The TDS will also move down the superpositioned CTL/PTL lines. The pilot will hold this heading until the TDS reaches the open center of the BRLS . When the TDS is between the inward points of the BRLS, the previously selected and armed stores will be automatically released. At this time the BRLS and CTL will disappear, indicating successful weapon release.

In addition to the symbols common to the other VDS modes, the "G" load is presented digitally and the "Time To Go" is shown as a decreasing bar on a linear scale. As shown, the pilot has about 32 seconds to correct the course and pitch deviations before weapon release.

1.9.3.6 Station Keeping Mode

Figure 12 depicts the suggested Stationkeeping format, which can be utilized during either the low level Terrain Avoidance Mode, or for high level air-to-air refueling in the Cruise Mode. These functions were identified in Mission No. 2, Penetrate, Escape and Carrier Rendezvous phases.

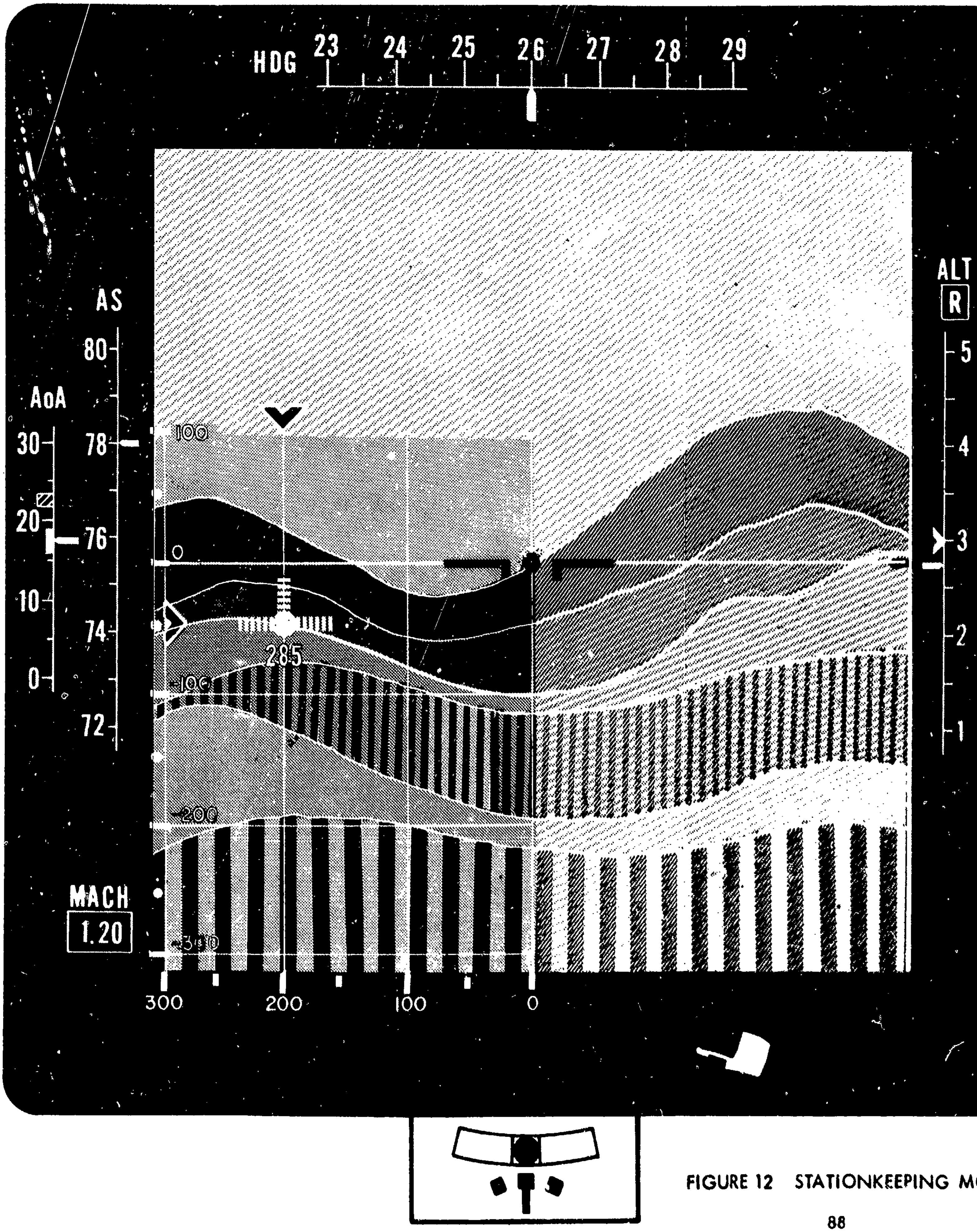


FIGURE 12 STATIONKEEPING MC

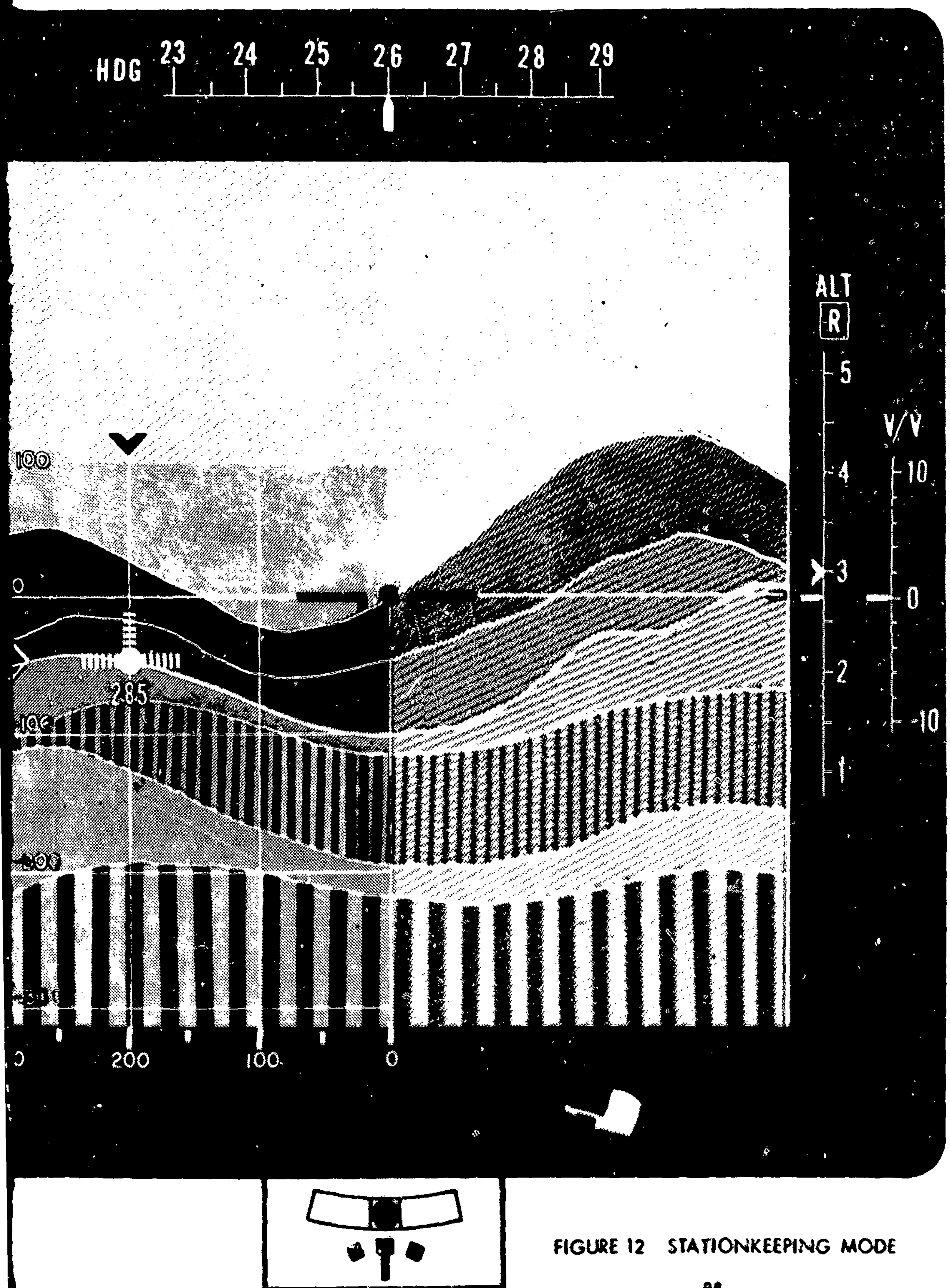


FIGURE 12 STATIONKEEPING MODE

This illustration shows the attack aircraft flying as wingman during the Penetration Phase. The common Terrain Avoidance features are displayed as previously shown in Figure 11, but with slightly decreased contrast and brightness, as this is now secondary information to the pilot. However, if the lead aircraft were suddenly lost, this data would become primary information at once! During the Mission No. 2 penetration, the pilot's primary function is to establish and maintain a (high-right) wingman slot during this mission phase. Prior to establishing his position, the pilot would set up his required grid quadrant (lower left in this case) and the desired altitude above and distance to the right of the lead aircraft. This command information would appear at the edge of the grid where the Command "V" symbols at 50 feet (above) and 200 feet to the left of his Aircraft Reticle and Velocity Vector symbols appear. The white Lead Aircraft Symbol (LAS) is shown at the intersection of the 50 and 200 foot grid lines, indicating that present position relative to the position of the lead aircraft is "on the button." The actual slant range (285 feet) between his and the lead aircraft is shown directly below the LAS symbol. The quantitative flight data presented on the periphery is common to previously discussed modes. Both the Dangerous Weather symbol and the Pull Up Command "X" would appear in this mode as appropriate.

A similar grid could be used for air-to-air refueling and superposed over the normal Enroute/Cruise Mode display. In this case the pilot would select the top half grid quadrant as he will be positioning his aircraft directly below and behind (slant range to) the tanker aircraft. The command indices would be positioned according to Naval flight safety standards for this flight mode.

1.9.3.7 Standoff Weapon Attack - Midcourse Mode

Figure 13 depicts the System Operator's VDS display during the midcourse guidance mode of the Standoff Weapon System (SWS) attack.

As hypothesized in Mission No. 2 scenario and flow diagrams, the S.O. monitors an automatic launch under zero-zero visibility. Since the SWS missile carries a high resolution TV sensor in this configuration, there was no "picture" available during this phase. However, all of the quantitative and qualitative data presented in the surround (frame) area were provided during the launch phase.

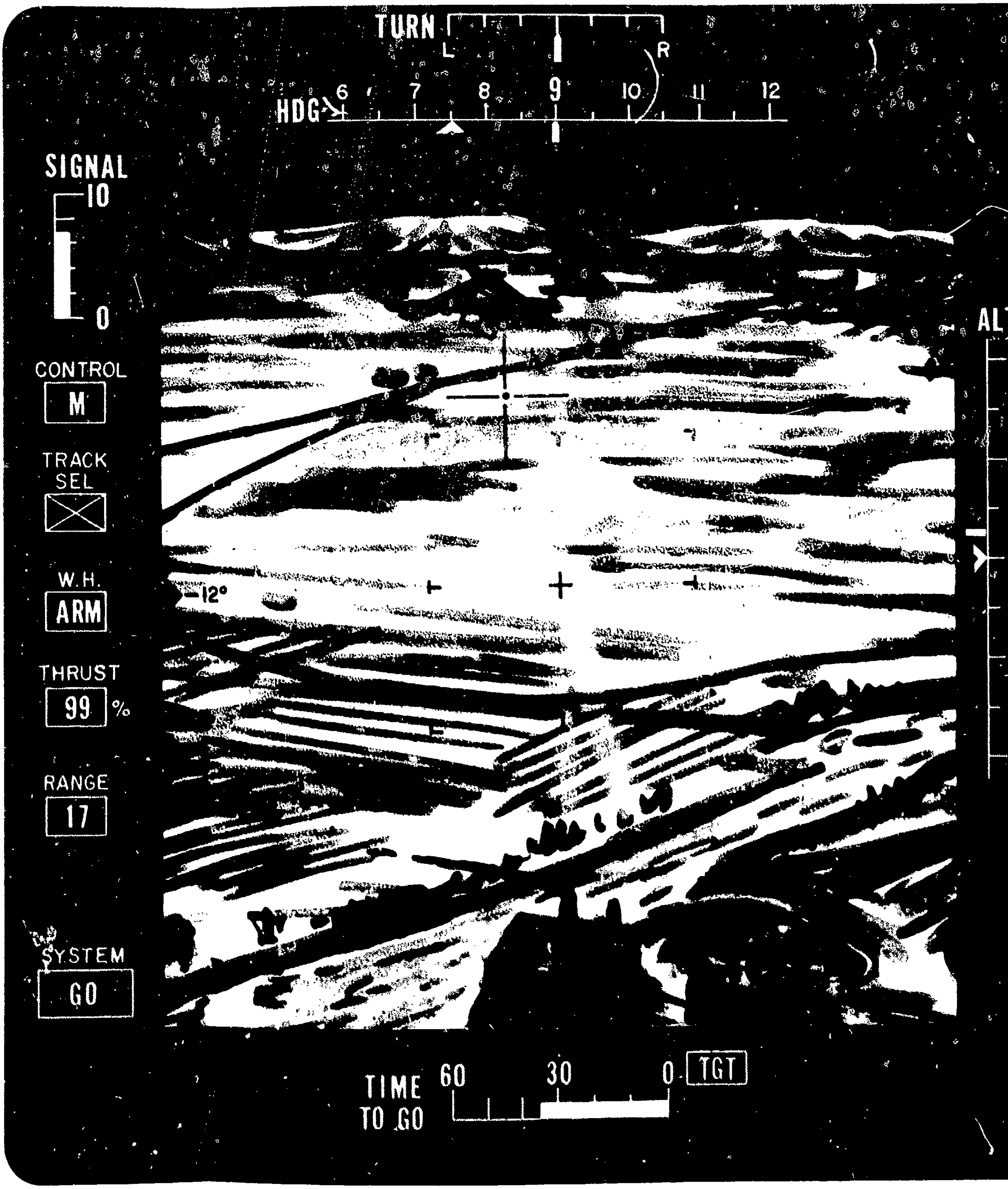


FIGURE 13 STANDOFF WEAPON ATTACK
MIDCOURSE GUIDANCE MODE

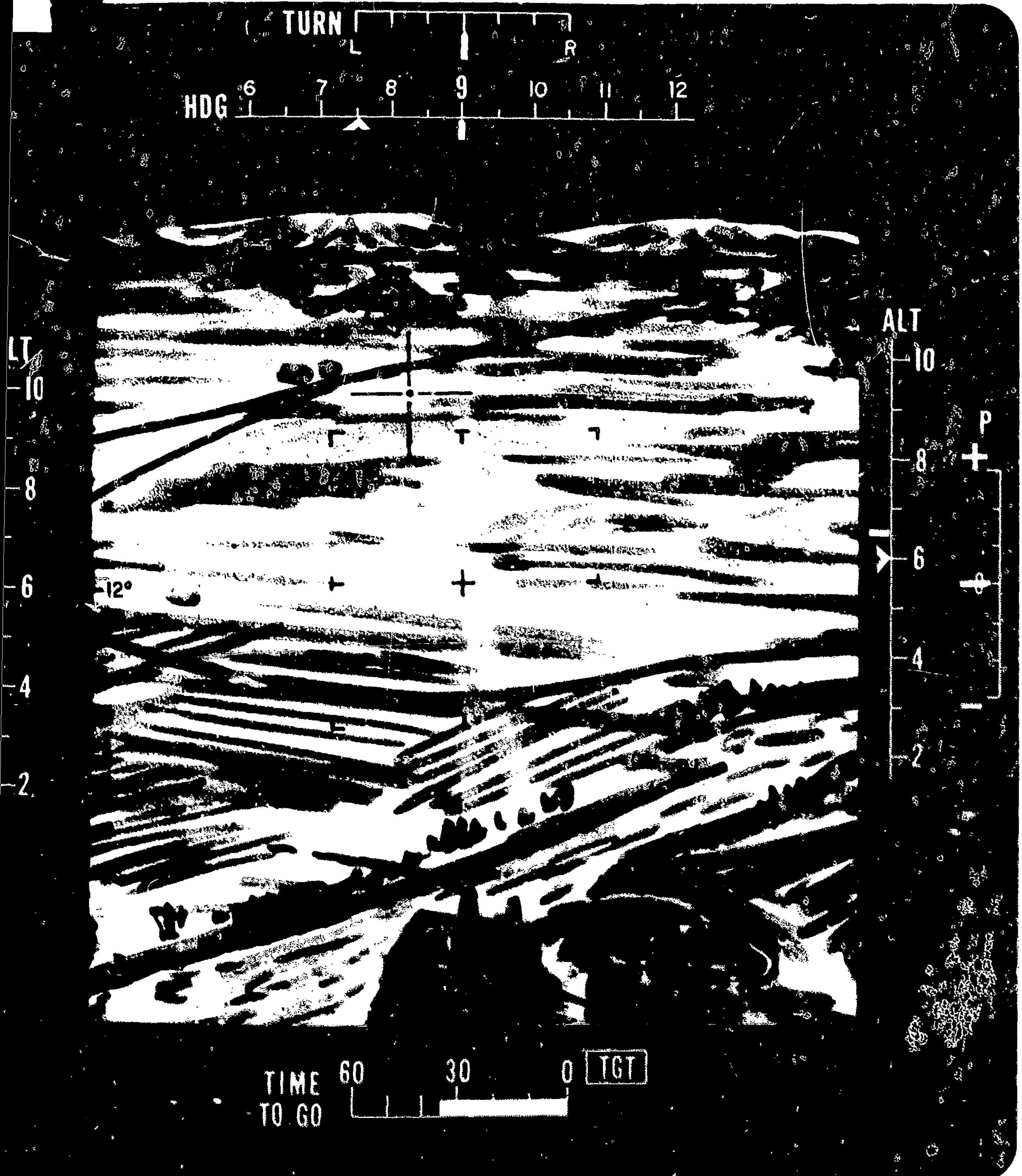


FIGURE 13 STANDOFF WEAPON ATTACK
MIDCOURSE GUIDANCE MODE

This figure illustrates the VDS display, using the 30° Field of View (FOV), shortly after the weapon pop-up maneuver has been completed. In the illustration, the closest checkpoint features have been slightly exaggerated in size to demonstrate the power of the TV lens at a moderate altitude. However, the 30° FOV and magnification shown are probably not obtainable at the same time.

In the picture area it can be seen that the S.O. has identified the target and placed the diamond shaped Target Designate Symbol (TDS) on the aiming point. Just below the TDS the black Aiming Reticle Symbol (ARS) is shown. The 10° FOV frame line symbol is depicted by the small black angles at 5° above, below, left, and right of the picture centerlines. These frame lines indicate the ground terrain that would be visible on the VDS if the S.O. would change to the 10° FOV at this instant. A 12° look-down angle is indicated at left edge of the picture centerline. Zero (0°) slew angle is indicated at the bottom center of the picture.

At this point the computer has solved the lateral offset (15°) and range calculations. A command heading of 75° versus the present actual heading of 90° is indicated. Since the Turn (yaw) index mark is still centered, the S.O. has not yet initiated the turn maneuver. A command altitude of 6,000 feet and actual altitude of 6,400 feet is shown in the right surround area. The Pitch (P) indicator shows a level flight condition at present.

At the top of the left surround area, the signal strength of the two-way data link is displayed as a moving bar over a linear scale. Reading downward we see that the "bird" is presently under manual (M) control; no terminal guidance (Track Sel) mode has been selected; the warhead (WH) is armed (ARM); maximum (99%) thrust is available; the range to the target is 17 miles; and the SWS (System) is in the "Go" condition. Time-to-go is displayed as a descending bar along with the next objective Target (TGT) displayed. These two information items are read together, such as "35 seconds to Target" (as shown), or so many minutes to Launch, or Navigation Checkpoint, as appropriate to the mission phase being flown and next objective.

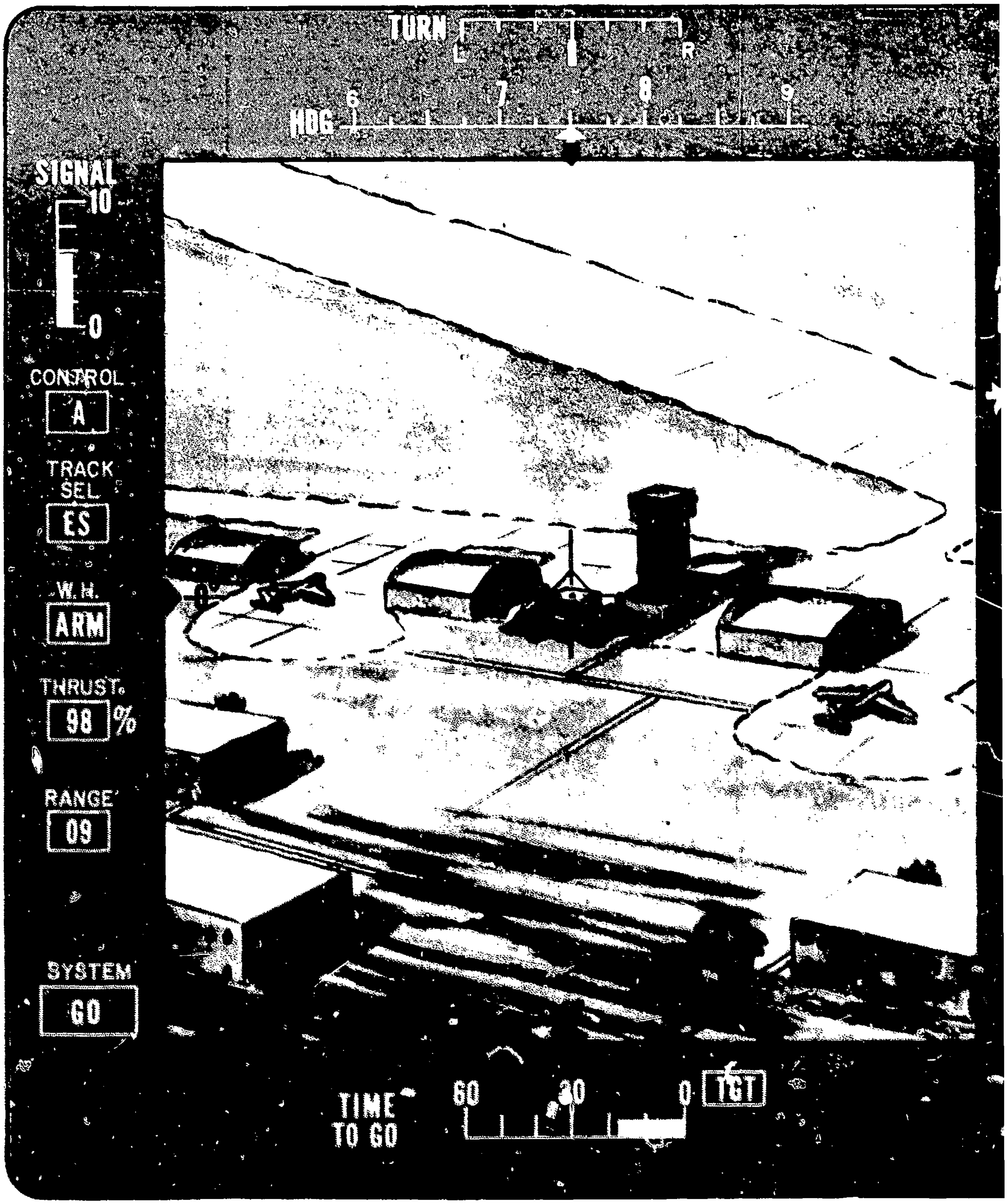


FIGURE 14 STANDOFF WEAPON ATTACK
TERMINAL GUIDANCE MODE

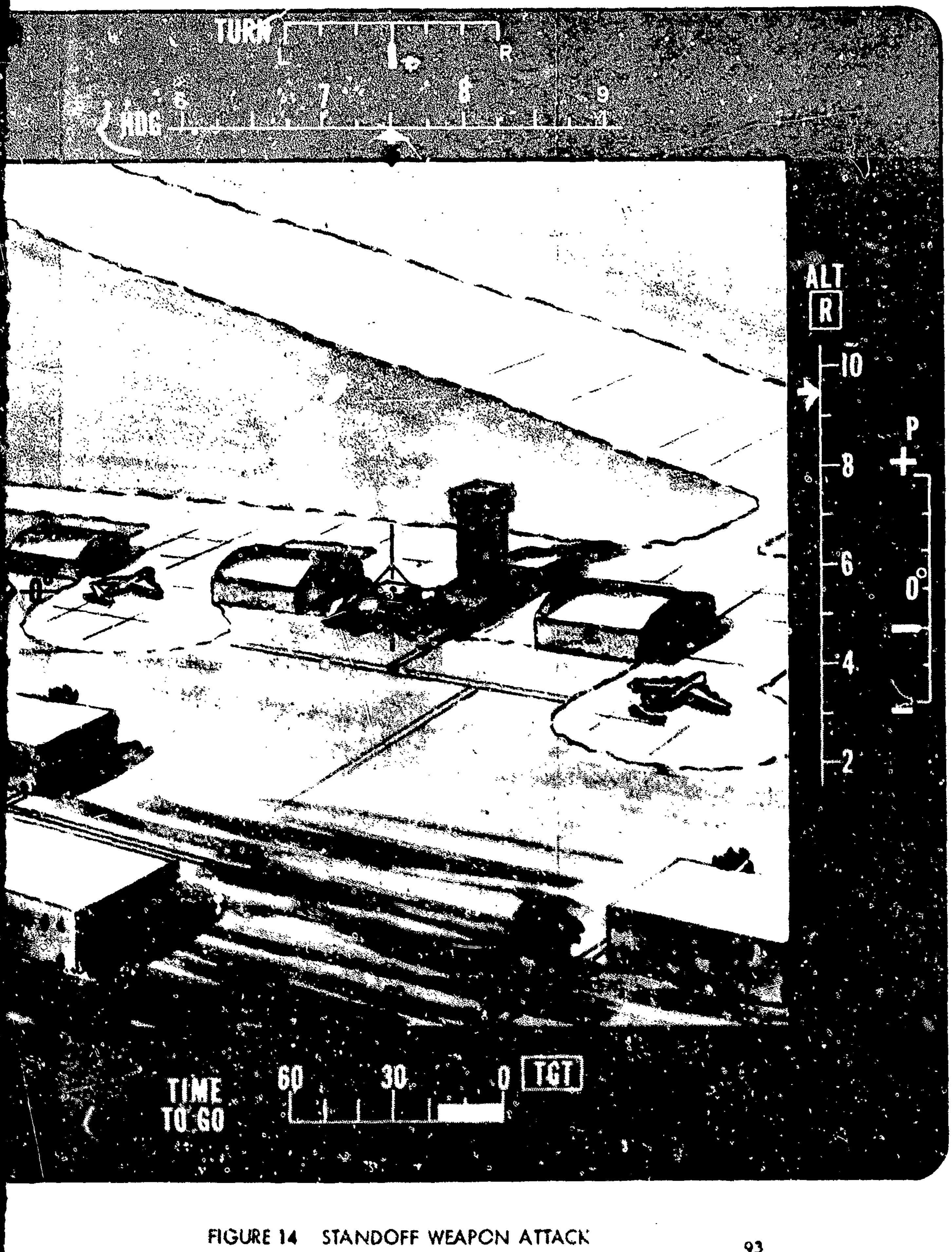


FIGURE 14 STANDOFF WEAPON ATTACK
TERMINAL GUIDANCE MODE

2.0 VERTICAL DISPLAY SYSTEM DESIGN REQUIREMENTS

2.1 SYSTEM DESIGN CONSIDERATIONS

This section derives the operational design parameters required for an advanced vertical display system with a multisensor high-resolution imaging capability for use in a 1985 era naval all-weather attack aircraft. A systems performance analysis was conducted to establish the range of acceptable display system performance characteristics based on functional and human factors requirements for compatibility with the advanced weapons and avionics systems which are envisioned for use in the next generation of attack aircraft. The result of the analysis is a set of optimum VDS design goals and performance specifications which can be used to evaluate various promising dot matrix display techniques in order to assess their applicability and select the optimum technique for an advanced vertical display system.

The functional requirements for a multisensor VDS to be used aboard a Navy attack aircraft in the 1985 time era must be based upon a detailed mission analysis, taking into consideration the aircraft characteristics and requirements along with the complement of weapons and avionics systems carried on board. The tactical aircraft of the 1980's, now in the conceptual and prototype phases of development, will have enhanced all-weather day/night capabilities for both air-to-ground attack and air-to-air missions. The trend of the future is toward higher speed and more maneuverable aircraft using weapons with greater range that permit increased standoff delivery distances. The enhanced performance capabilities will be due largely to increased capabilities of future avionics systems such as longer range, higher resolution multifunction radars, high-resolution forward-looking IR (FLIR), and high-resolution video systems. It is these major subsystems which will have the greatest impact on VDS design requirements.

A survey of the high-resolution multisensor imaging sensors was conducted in order to identify the most demanding (worst case) performance parameters and operational characteristics, and insure that the design parameters which are established for the VDS are based on these conditions and are compatible with them.

The future trend in radar system design is toward a single antenna multifunction unit using electronic beam steering with solid state circuitry to achieve high switching rates with high beam and frequency agility. This type of radar system will have a low level flight penetration capability using terrain following and avoidance techniques, with terrain mapping for use in navigation and target location, and ground target ranging and tracking for weapon delivery purposes. The air-to-air role requires a long-range search detection and tracking capability with an automatic moving target indicator to separate low flying aircraft from ground clutter, and semiactive missile guidance for weapon delivery. Other functions such as stationkeeping, radar altimeter, doppler navigation, electronics countermeasures, and beacon interrogation (IFF) will also be required. These diverse functions require sophisticated data processing equipment and a display system that conveys the full resolution capabilities of the radar system. Future system performance specifications indicate a ground mapping resolution capability of 40 feet over a 10x10 mile area which could effectively utilize a display with 1500 scanning lines, with digital scan conversion used where low data rates would cause large area flicker problems, or where the sensor and display formats are incompatible.

Forward-Looking Infrared systems (FLIR) are continuing to offer improved detection capability for target acquisition and weapon delivery purposes under poor visibility or nighttime conditions. Resolution of the advanced systems is approximately 800 TV lines, which is obtained by use of several hundred simultaneous scanning detectors with improved signal-to-noise ratios that permit imaging approximately 10 shades of gray.

High resolution video systems are now being developed for long range target recognition systems for IFF purposes and for weapon delivery (such as angle rate bombing and missile guidance) and fire-control systems. The trend here is toward the use of high resolution sensors (1000 TV lines) with 10 shades of gray imaging capability.

It is evident that a multisensor VDS that is to be operational aboard an attack aircraft in the 1985 time period must have a resolution capability of at least 875 to 1000 TV lines and incorporate a digital scan conversion

capability in order to be consistent with the performance expected from the multifunction radar, FLIR, and high resolution video systems that are expected to be available in that time period. The results of the multisensor survey are given in detail in reference 12 and are summarized in terms of resolution, gray scale and MTF requirements in Table 14.

TABLE 14 MULTISENSOR OPERATIONAL CHARACTERISTICS

	Type of Sensor System	Resolution TV Lines Picture Height	Shades of Gray	MTF
1.	Low Light Level TV (LLTV)	200- 600	8	0.1 @ 15 cycles/MR
2.	High Resolution Vidicon	400-1000	10	0.1 @ 50 cycles/MR
3.	Forward Looking IR (FLIR)	400- 800	10	0.5 @ 4 cycles/MR
4.	Multimode Radar	1500	8	0.1 @ 3 cycles/MR

Table 14 indicates that the high resolution vidicon sensor system is the highest performing and therefore imposes the most demanding display performance requirements, particularly with regard to the MTF requirements. This is further illustrated in figure 15[13] which is a performance comparison of the high-resolution video sensors. This sensor system will therefore be used in the systems analysis to determine the contrast and resolution requirements of the VDS. The following subsections discuss the detailed aspects of the human factors and functional requirements of the VDS in order to establish a set of preliminary performance specifications.

2.2 HUMAN FACTORS CONSIDERATIONS

In the context of display requirements, Morgan[14] succinctly describes the essential aspects of displays when he states: "There is much more to designing a good visual display than merely making it visible; the operator must understand the presented information, and, with minimum effort and delay, convert it onto correct decisions and/or control actions. This means that the display must be designed to suit the particular conditions under which it will be used, the method of use, and the purposes it is to serve."

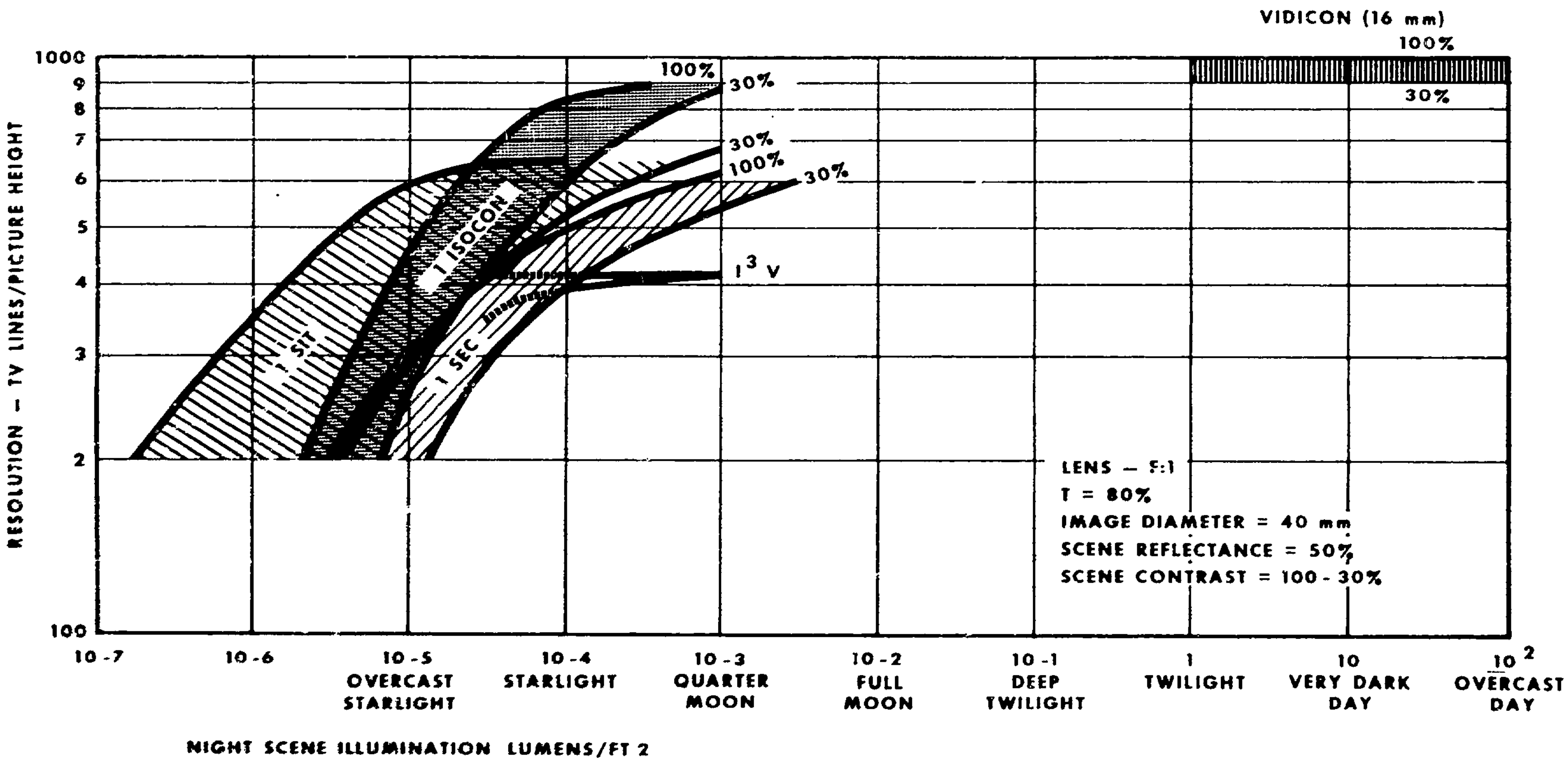


FIGURE 15 A PERFORMANCE COMPARISON OF VIDEO SENSORS

This subsection contains a discussion of the visual parameters which are pertinent to the presentation of Vertical Display System information and will develop the resolution and contrast requirements based on MTF analysis. The human factors considerations associated with display brightness, gray scale, refresh rate and symbology requirements will also be discussed.

2.2.1 CONTRAST AND SIZE REQUIREMENTS OF THE HUMAN EYE

The resolving power of the eye is defined and measured in terms of ability to detect small objects and distinguish fine detail. The resolving power, or visual acuity of the normal human eye varies greatly, depending upon the object brightness, distribution of radiant energy, background luminosity, contrast, and duration of the stimulus object.

2.2.1.1 Size

Acuity is usually specified as the reciprocal of the minimum visual angle expressed in minutes of arc while the criterion for detection in classical perceptual studies has been the 50-percent threshold; i.e., a target of sufficient size which will be detected 50 percent of the time. When the target characteristics noted above are held constant, doubling the size of a target will normally increase the probability of detection from 50 percent for threshold targets to approximately 99 percent.

Providing that sufficient exposure time is available, visual acuity is dependent upon brightness, background contrast, and the surrounding brightness ratio of the object or display being viewed. This latter factor is of primary importance to the aircraft pilot who must monitor the cockpit displays while attending to the real world outside the cockpit.

Figure 16[15] shows the contrast demand requirements of the human eye to resolve tri-bar test patterns for two display brightness values (20 fL and 300 fL). Both curves indicate that the maximum eye response occurs at approximately 10 to 20 cycles/mm on the retina, with the brighter display requiring less contrast to achieve any selected value of spatial frequency and cutting off at a higher value. A different curve results for each viewing distance and brightness level. Figure 17[15] shows how the limit of resolution varies for

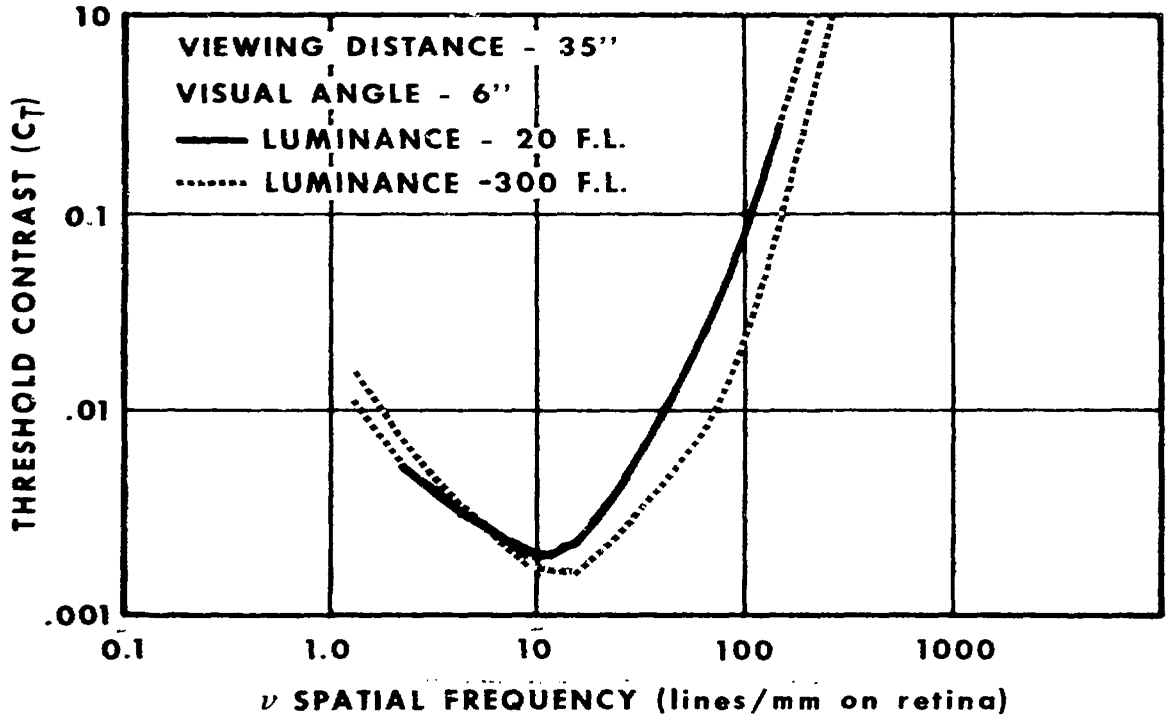


FIGURE 16 CONTRAST SENSITIVITY FOR SINE-WAVE TEST OBJECTS

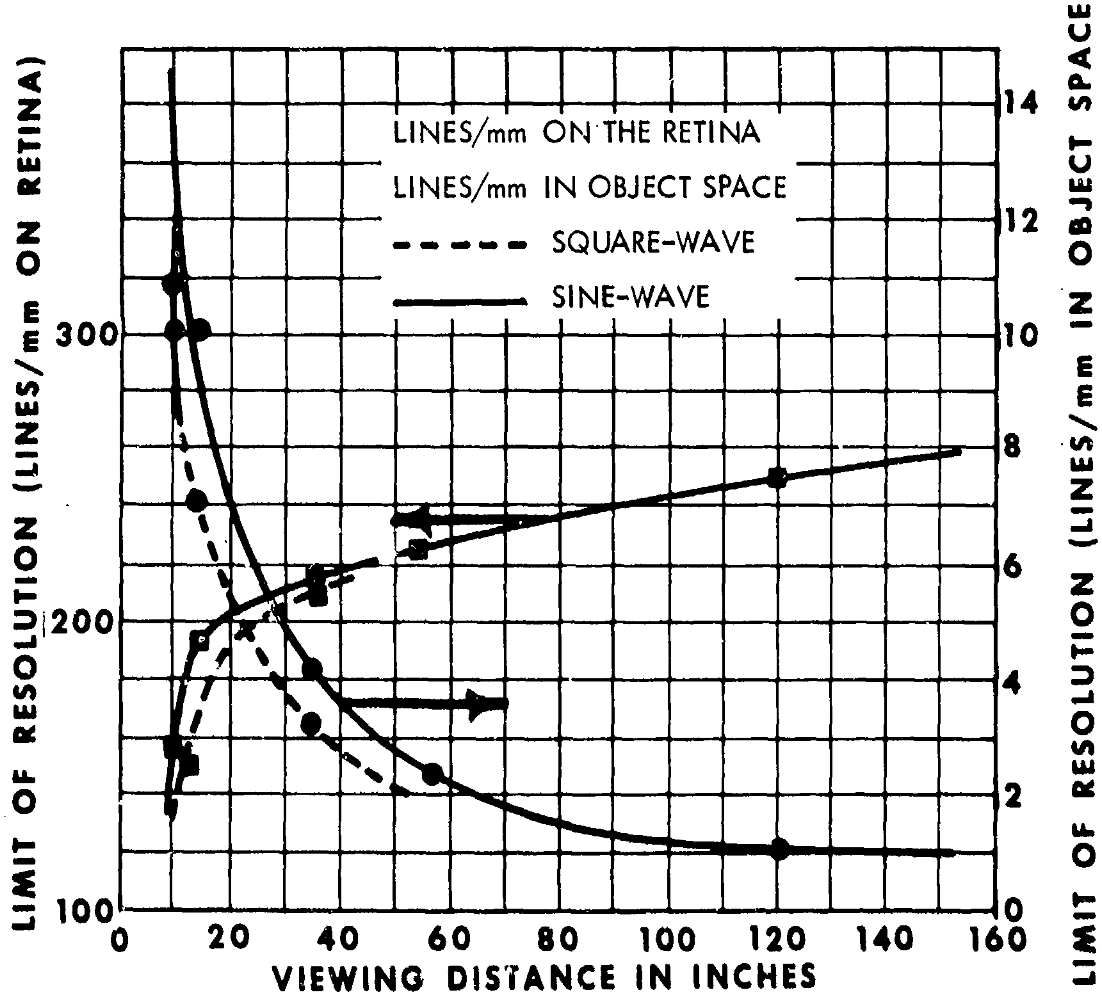


FIGURE 17 LIMIT OF RESOLUTION AS A FUNCTION OF VIEWING DISTANCE

each viewing distance for sine wave and square wave test patterns for a particular value of display brightness (~20 fL).

2.2.1.2 Contrast

The contrast of a target is a measure of its brightness relative to its background. It is defined by

$$C = \frac{B_t - B_b}{B_b}$$

where B_t is the brightness of the target and B_b is the brightness of the background. The contrast can range from -1 through 0 to infinitely large. Within the range of -1 to 0 it is termed "negative contrast," the target being darker than the background.

2.2.1.3 Gray Scale

Another concept closely related to contrast and contrast ratio is that of shades of gray. As usually defined, the number of shades of gray between the brightest and darkest elements of a scene or of a display is the number of square-root-of-two steps, counting both the background and the highlight. Thus, a contrast ratio of 1.414 corresponds to two shades of gray, while a contrast ratio of 2.0 is equivalent to three shades of gray, etc.

In an analysis of a VDS system, it is important to consider the number of shades of gray required to facilitate the detection and recognition of video information. Figure 18[13] is a plot of target detection time vs gray scale for a video system with 550 scanning lines. This graph indicates that the time required for target detection decreases as the number of gray shades increases up to approximately 7 shades of gray and then levels off. However, it is suggested that to facilitate the operator's task of target recognition, at least 7 shades of gray is a minimum, and 8 to 10 shades are desirable for target recognition purposes for cockpit displays.

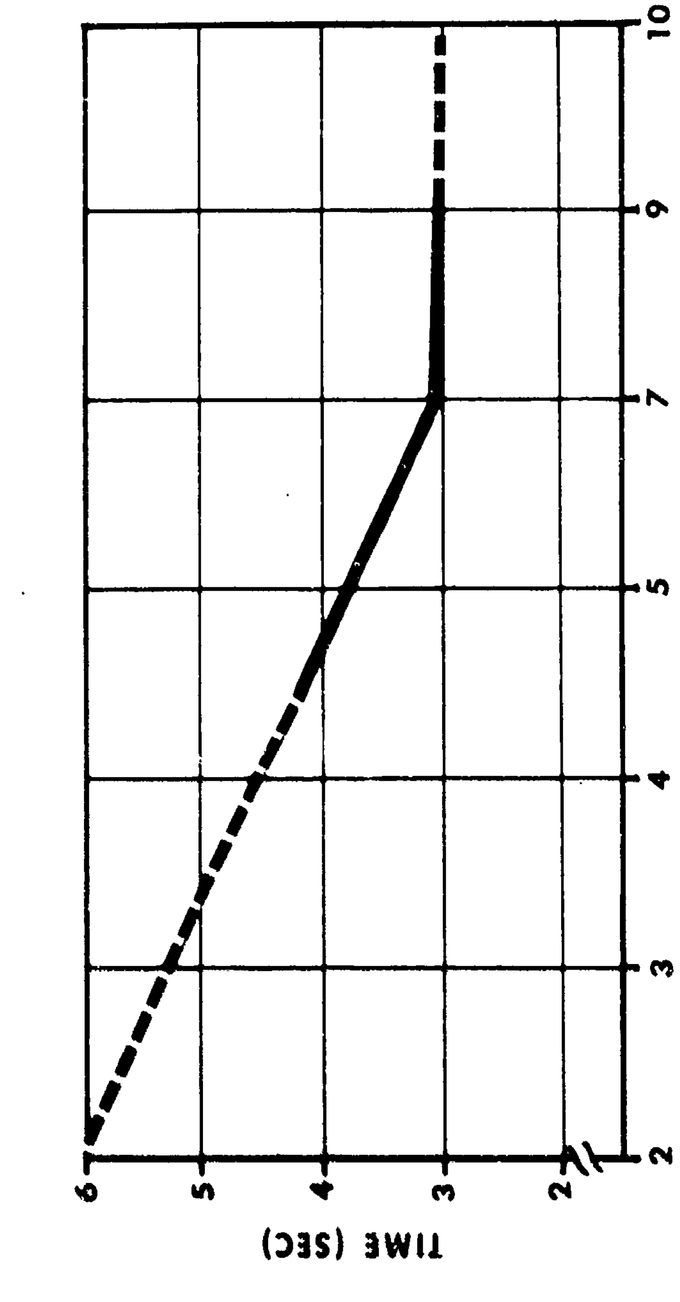


FIGURE 18 TARGET RECOGNITION TIME AS A FUNCTION OF SHADES OF GRAY

2.2.1.4 Surround Illumination

Brightness ratio is defined as "The ratio of the brightness of the object being viewed in relation to that of the area surrounding the object." Morgan[14] refers to this effect in terms of operator "adaption level." He indicates that if visual displays must be read by people who have just been exposed to high levels of brightness, the level of display brightness should be higher than normal (adaptive) brightness; i.e., at least 0.01 as bright as the pre-exposure field. Military Standard 1472A, paragraph 5.2.4.6, indicates that surfaces immediately adjacent to scopes shall be between 10% and 100% of screen background brightness.

The effects of surrounding illumination on visual performance has been reviewed by Ireland.[16] In a subsequent experiment, he tested four surround-to-background brightness ratios of 0:1, 1:1, 10:1, and 100:1. Regarding the practical implications of his experimental data, he states:

> "In operational display facilities, it is never desirable to have surrounds that are considerably brighter than the backgrounds. However, in many situations, a surround somewhat lighter than the background is virtually unavoidable, and in some cases (such as aircraft cockpits) surround-to-background brightness ratios may be quite large."

Other evidence is demonstrated by experiments conducted by the Life Sciences personnel of North American Aviation regarding the effects of high levels of task brightness, and the effects of repeated changes in task brightness levels.[17] Miller and Middleton note that, considering that current instrument panel brightness levels are generally less than 30 foot-lamberts, appreciable changes in light adaption must occur when the field of view is alternately directed within and outside the vehicle. External light sources encountered in normal aircraft environments range from: blue sky (2,000 fL), average earth surface (6,000 fL), to reflection off clouds (10,000 to 13,000 fL).

In the North American Aviation study, four task illumination brightness levels of 3, 30, 300 and 3,000 fL were presented alternately with a 6,000 fL adaption source. The results indicated that average performance was not significantly degraded by exposure to high brightness on the order of 6,000 fL, when the normal task brightness is at least 30 fL, and adequate figure/background contrast is provided. However, when the normal task brightness was as

low as 3 fL, alternate exposures to the 6,000-fL level produced marked transitory effects and a significant reduction in average performance. At the lowest task level, performance was reduced by 90% for 30 seconds subsequent to high brightness exposure, and required 100 seconds for complete recovery to the pre-exposure level. The authors show that both visual acuity and contrast sensitivity are reduced by exposures to brightness higher than the task and conclude that:

> "If panel contrast is well above the threshold, increases in panel brightness beyond 30 fL will not significantly improve (operator) performance. Additionally, no improvement in recovery time is obtained by providing additional illumination beyond 30 fL. Therefore, the designer must expect the operator to perform below his average for some 20 seconds after being exposed to a severe change in task brightness." (e.g., "Head out" at 6,000 fL to "Head in" at 30 fL.)

2.2.1.5 Flicker

Display flicker has been a problem with cockpit displays in many instances, but within the brightness range required for a VDS display, it has been demonstrated that 60 repetitions per second is a safe lower limit which permits satisfactory viewing. This is illustrated in Figure 19[13] where the critical flicker frequency (CFF) is plotted as a function of display brightness and object area. Higher display brightness values or larger area object stimuli cause higher values of CFF.

2.3 DISPLAY RESOLUTION AND CONTRAST REQUIREMENTS

The resolution and contrast requirements of a cockpit display system can best be determined by means of a modulation transfer analysis of the complete imaging system which the display is part of. In the case of the VDS display it has been determined that the most demanding MTF imaging performance requirements of the display system are imposed by operating with a high resolution vidicon sensor system of the type used for target identification (IFF) and weapon delivery purposes. For comparison purposes an MTF analysis was conducted for a continuously scanned and digitally scanned system.

2.3.1 MTF Analysis for Continuously Scanned System

An MTF analysis was made of a complete high resolution vidicon imaging system with the results plotted in Figure 20. The system consists of the

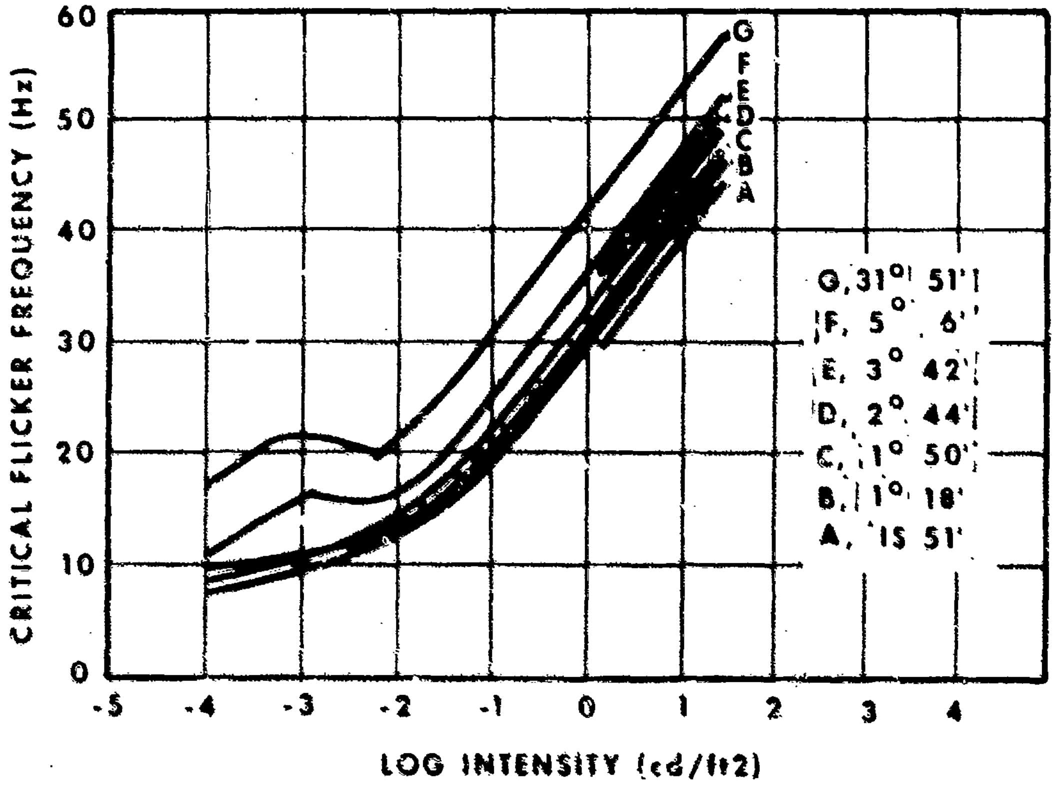


FIGURE 19 CFF, AREA AND BRIGHTNESS

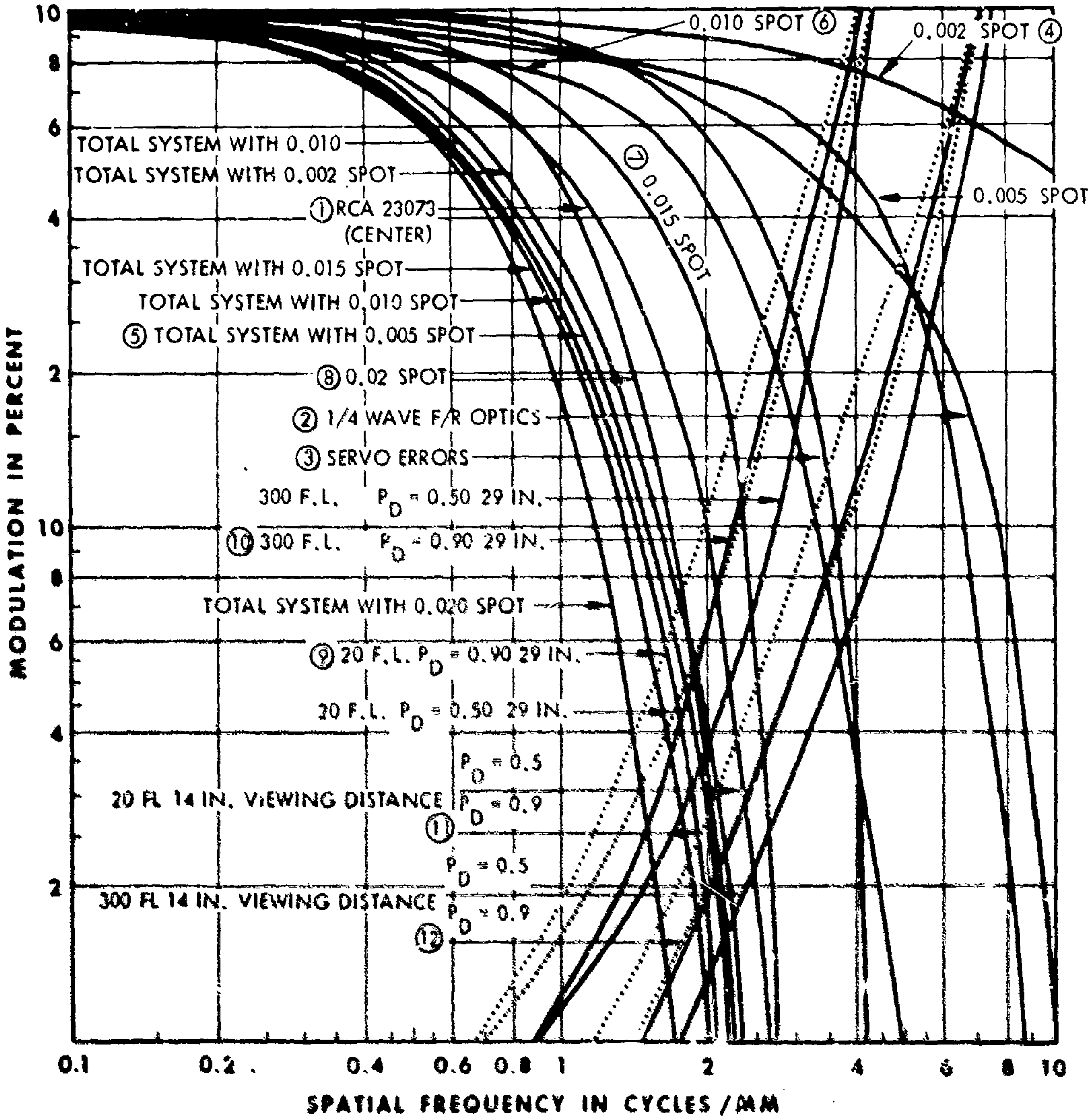


FIGURE 20 MTF ANALYSIS OF CONTINUOUSLY SCANNED SPOT SYSTEM

RCA 23073 vidicon, curve 1; an F/12 1/4-wave optical system, curve 2; a servo tracker system with 2 arc second RMS error, curve 3; and a continuously scanned display system with scanning spot sizes of various dimensions (0.002, curve 4; 0.005, curve 5; 0.010, curve 6; 0.015, curve 7; and 0.020 inch, curve 8).

The MTF response of a continuously scanned gaussian spot is the absolute value of the Fourier transform of the aperture shape which can be calculated from the following expression:

$$MTF = e^{-\frac{2\pi^2 f^2 w^2}{8\,(0.693)}} \qquad \text{(Ref 18)}$$

where f = spatial frequency in cycles/mm

w = half intensity spot width

The MTF response of the diffraction limited optical system was calculated from the following expression:

$$MTF = \frac{v\lambda F}{D} \qquad \text{(Ref 18)}$$

where v = spatial frequency

λ = wavelength of light

$\frac{F}{D}$ = F number

The MTF response characteristic for an uncompensated image motion in the focal plane due to servo tracking errors was calculated from the following expression:

$$MTF = \frac{\sin \pi aK}{aK} \qquad \text{(Ref 18)}$$

where a = magnitude of image motion

K = spatial frequency

The contrast demand function of the human eye was calculated for a square wave input at the normal cockpit viewing distance of 29 inches, with a probability of detection of 0.9 for 2 values of screen brightness, curve 9, 20 fL, and curve 10, 300 fL. Curves 11 and 12 are for the same conditions at a 14-inch viewing distance for 20 and 300 fL, respectively. The area bounded by each of the total system performance curves and the contrast demand curves of the

eye is a measure of the total imaging capabilities of each system, and the intersection of the two curves determines the maximum or cutoff angular resolution capabilities of each system.

The results of this analysis are tabulated in Table 15 for the two viewing distances, 14 and 29 inches, and two values of screen brightness, 20 and 300 fL. This table lists the maximum angular resolution in arc seconds attainable by each diameter spot and the linear dimension of one resolution at a distance of 10 nautical miles. The percentage degradation in cut off angular resolution for each system compared to the 0.002-inch diameter spot is also given. This table shows that the performance starts to degrade at a greater rate between 0.010-inch and 0.015-inch spot diameters and suffers a very large performance degradation between 0.015-inch and 0.020-inch spot diameters.

2.3.2 MTF Analysis for a Digitally Scanned System

The MTF response of a digitally scanned system is derived in Appendix I, with the results shown in Figure 21. This graph contains a plot of a continuously scanned system, curve 1, with a beam 1/2 diameter equal to γ and two digitally scanned systems with the same spot diameter which move different increments during the scanning process. Curves 2 and 3 represent the maximum and minimum response respectively of a digitally scanned system with the beam movement equal to two beam half widths ($\Delta X = 2Y$), which is typical of the vertical axis of a CRT continuously scanned system. Curves 4 and 5 represent the maximum and minimum response respectively of a digitally scanned system with the beam movement equal to four beam half widths ($\Delta X = 4Y$), which is representative of a digitally scanned dot matrix display where the spot diameter is equal to the dark area in between spots. Maximum and minimum response curves correspond to having the phase relationship of the tri bar test target completely in or out of sync with the read out beam. Any other phase relationship would result in an MTF curve falling between these two extremes. The positive and negative going spikes occurring at distinct spatial frequencies which are harmonics of the cut off frequency where the sampling theorem (minimum, 2 samples per cycle) is no longer satisfied.

An MTF analysis of a digitally scanned dot matrix display system was performed with the results plotted in Figure 22. The same vidicon sensor (curve 1), servo system (curve 2) and optical system (curve 3) were used as for the

TABLE 15 COMPARISON TABULATION FOR OVERALL SYSTEM IMAGING PERFORMANCE

(CONTINUOUSLY SCANNED SPOT)

$P_D = 0.9$

		2 MIL SPOT DIA		5 MIL SPOT DIA		10 MIL DIA		15 MIL SPOT DIA		20 MIL SPOT DIA	
VIEWING DISTANCE INCHES	SCREEN BRIGHTNESS FOOT-LAMBERTS	ANGULAR RESOLUTION $\widehat{SEC}$	LINEAR RESOLUTION AT 10 N. MI. RANGE IN INCHES	ANGULAR RESOLUTION $\widehat{SEC}$	LINEAR RESOLUTION AT 10 N. MI. RANGE IN INCHES	ANGULAR RESOLUTION $\widehat{SEC}$	LINEAR RESOLUTION AT 10 N. MI. RANGE IN INCHES	ANGULAR RESOLUTION $\widehat{SEC}$	LINEAR RESOLUTION AT 10 N. MI. RANGE IN INCHES	ANGULAR RESOLUTION $\widehat{SEC}$	LINEAR RESOLUTION AT 10 N. MI. RANGE IN INCHES
29	20	4.58	16.2	4.72 (-3.05%)	16.7	4.85 (-5.9%)	17.15	5.17 (-12.9%)	18.3	5.85 (-27.7%)	20.7
29	300	4.37	15.5	4.45 (-1.83%)	15.75	4.58 (-4.8%)	16.2	5.01 (-14.7%)	17.7	5.64 (-29.1%)	20
14	20	2.9	13.58	4.12 (-5.64%)	14.53	4.37 (-12%)	15.5	4.58 (-17.5%)	16.2	5.15 (-32.1%)	18.3
14	300	3.83	13.5	3.9 (-1.83%)	13.8	4.11 (-9.92%)	14.5	4.37 (-14.1%)	15.5	5.01 (-30.8%)	17.7

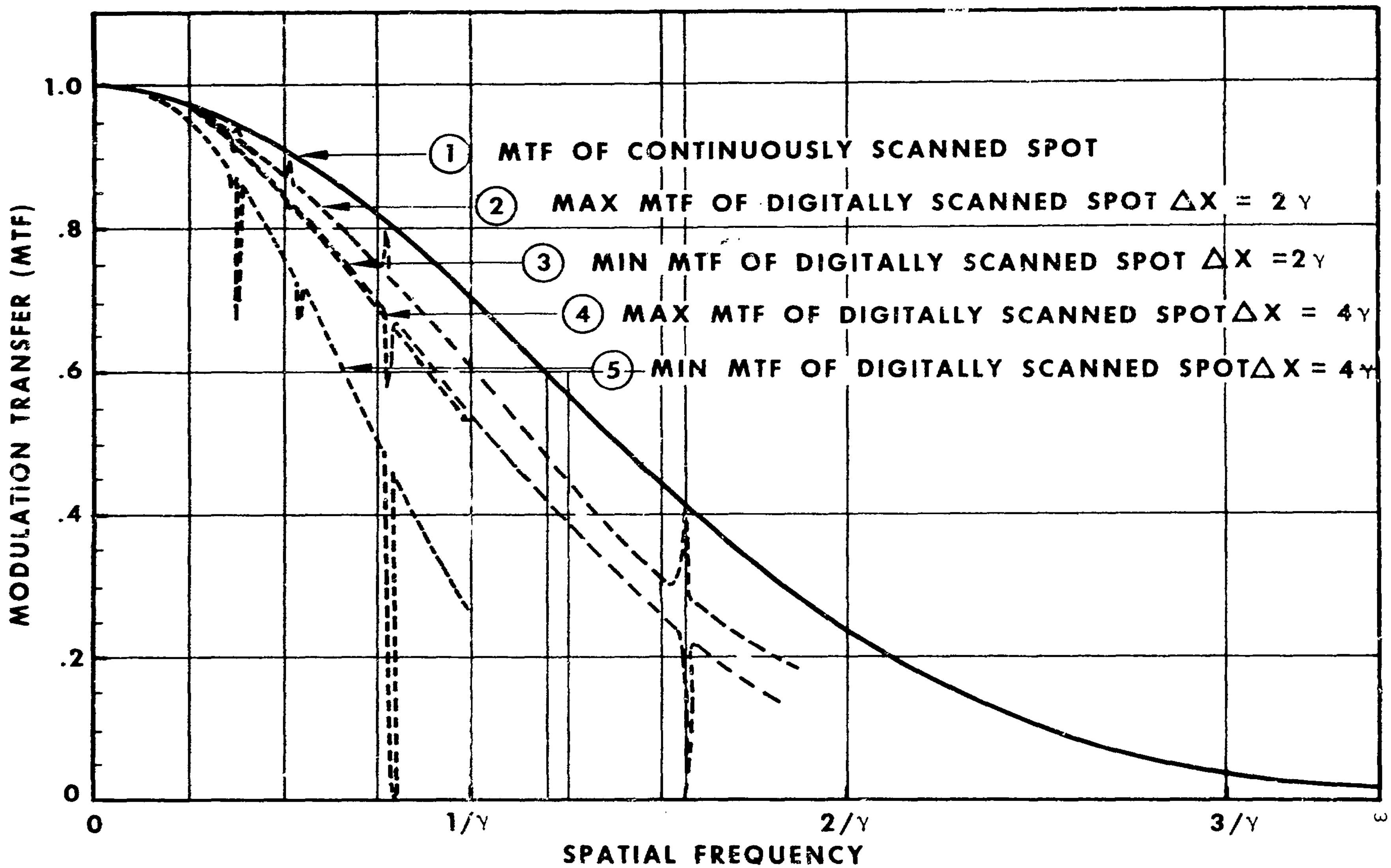


FIGURE 21 COMPARISON OF MTF PERFORMANCE OF DIGITALLY VS CONTINUOUSLY SCANNED SPOT

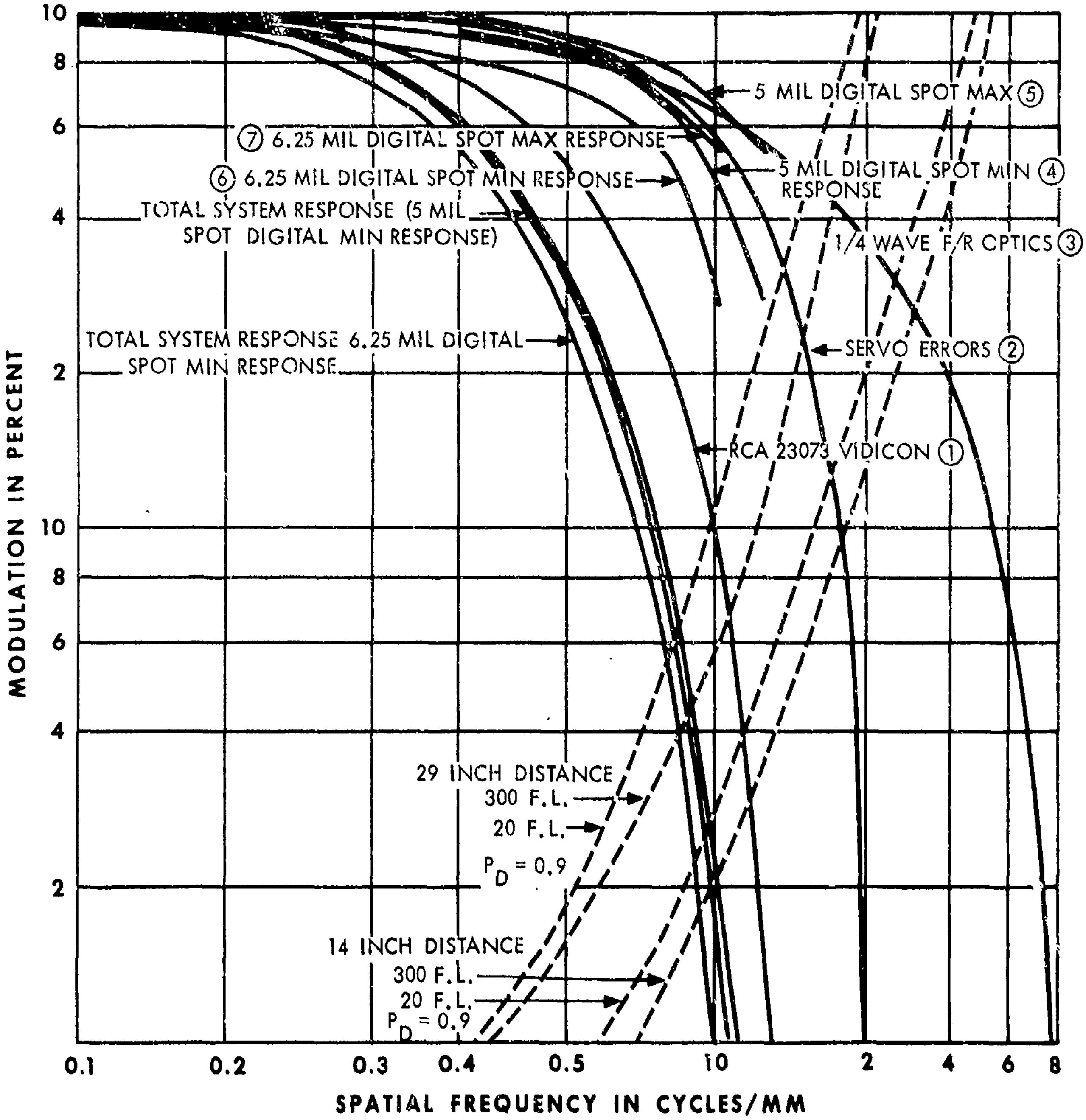


FIGURE 22 MTF ANALYSIS OF DIGITALLY SCANNED SPOT SYSTEM

continuously scanned system, but the dot matrix display system used a digitally scanned spot with beam movement equal to 4 half widths ($\Delta X = 4\gamma$). Curves 4 and 5 represent the minimum and maximum response for a spot diameter of 0.005 inch (100 dots per inch) and curves 6 and 7 are for a spot diameter of 0.00625 inch (80 dots per inch). The results of the analysis are tabulated in Table 16 for the 29-inch and 14-inch viewing distance for 20 fL and 300 fL screen brightness values. The angular resolution in arc seconds is shown along with the dimensions of a resolution element (in inches) at a distance of 10 nautical miles. The percent degradation of the system cutoff resolution performance is also indicated relative to the 0.002-inch spot diameter continuously scanned system. This tabulation indicates that the 0.005-inch spot diameter digital scan in the worst case (minimum response) is approximately equal to the response of a 0.010-inch continuously scanned spot. This is shown graphically in Figure 23 where the digital and continuously scanned spots are compared to the 0.002-inch continuously scanned case. The 80-dots-per-inch digital scan corresponds in the worst case (minimum response) approximately to a 0.0125 mil continuously scanned spot.

The MTF analysis was based on laboratory data on stationary images. In a high speed attack aircraft some further degradations would occur due to vibration and/or buffeting during low altitude high speed flight. It is felt, therefore, that a dot matrix display with a digital read out using a 0.005-inch beam (100 dots per inch) should be completely compatible and is considered optimum for use with a high resolution 1023 TV line vidicon sensor system. The 0.00625-inch (80 dots per inch) digital system is considered a lower bound of acceptability for high resolution imaging systems where an 875 TV line vidicon sensor system is used.

2.3.3 Number of Scanning Lines

The number of active scanning lines used in the display system must be compatible with the requirements of the high resolution sensor system with which it must interface. Figure 24[13] shows a plot of the target recognition time as a function of horizontal resolution. The solid curve is based on measured values up to 550 TV lines and is extrapolated by the dashed curve at higher values of resolution. Figure 25[13] is a similar plot showing how the

TABLE 16 COMPARISON TABULATION FOR OVERALL SYSTEM IMAGING PERFORMANCE (DIGITALLY SCANNED SPOT)

$P_D = 0.9$

		100 DOTS/INCH 5 MIL SPOT DIA				80 DOTS/INCH 6.25 MIL SPOT DIA			
		MIN RESPONSE		MAX RESPONSE		MIN RESPONSE		MAX RESPONSE	
VIEWING DISTANCE INCHES	SCREEN BRIGHTNESS F.L.	ANGULAR RES $\widehat{SEC}$	LINEAR RES IN.	ANGULAR RES $\widehat{SEC}$	LINEAR RES IN.	ANGULAR RES $\widehat{SEC}$	LINEAR RES IN.	ANGULAR RES $\widehat{SEC}$	LINEAR RES IN.
29	20	4.85 -5.9%	17.15	4.8 -4.81%	17.0	5.01 -9.38%	17.7	4.85 -5.9%	17.15
29	300	4.58 -4.8%	16.2	4.51 -3.2%	15.9	4.72 -8.02%	16.7	4.58 -4.8%	16.2
14	20	4.37 -12%	15.5	4.23 -8.45%	14.98	4.48 -14.4%	15.8	4.37 -12%	15.5
14	300	4.11 -9.92%	14.5	4.02 -4.97%	14.2	4.24 -10.7%	15	4.02 -9.92%	14.2

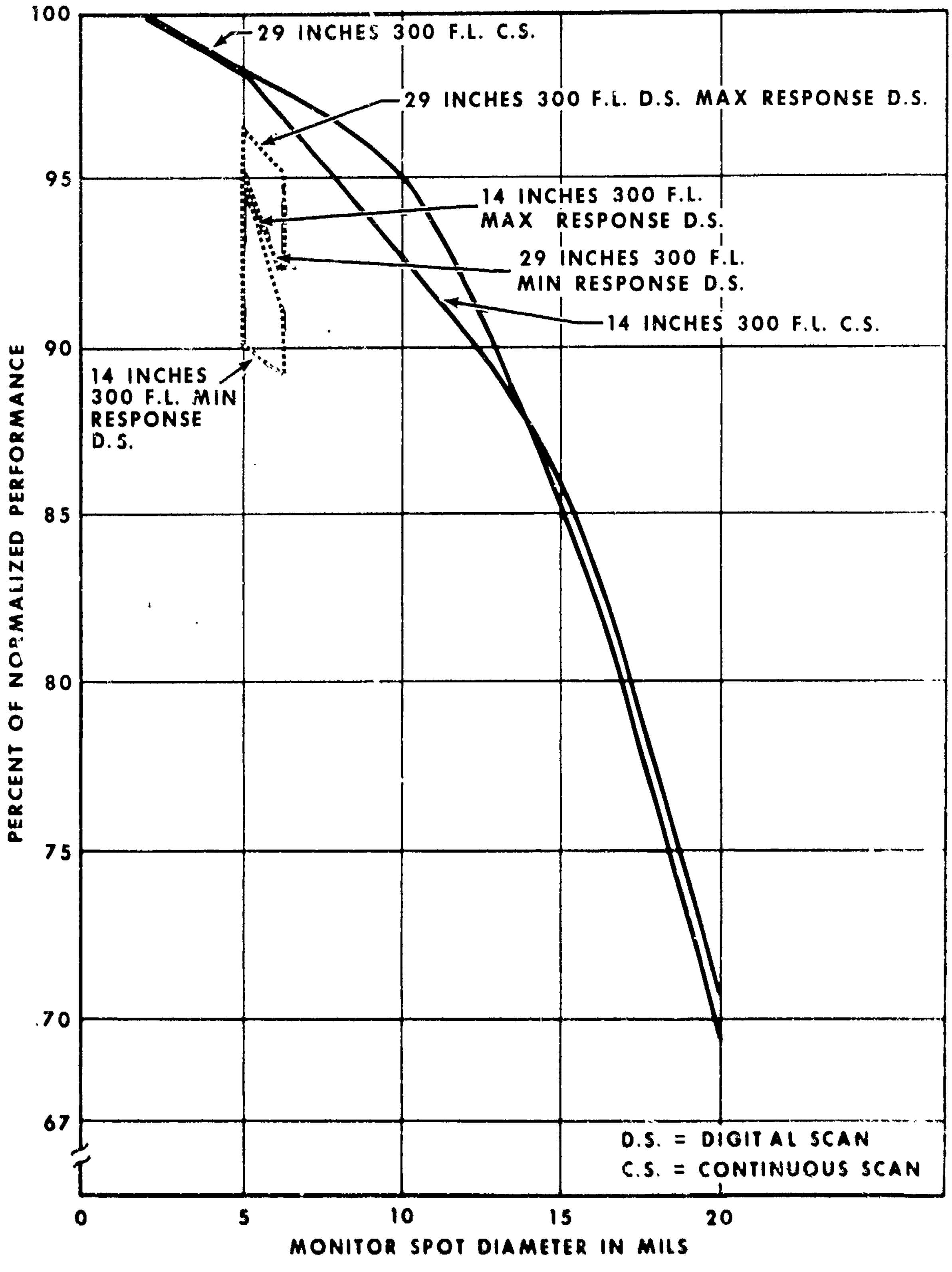


FIGURE 23 PERFORMANCE COMPARISON OF DIGITAL AND CONTINUOUS SCANNED SYSTEMS

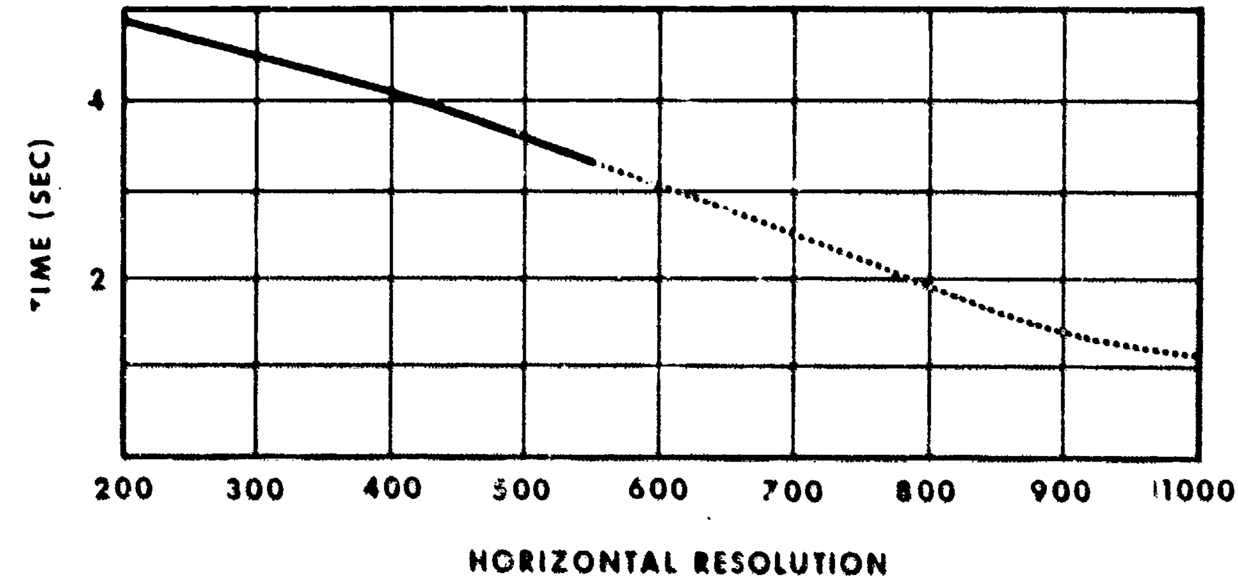


FIGURE 24 TARGET RECOGNITION TIME AS A FUNCTION OF RESOLUTION

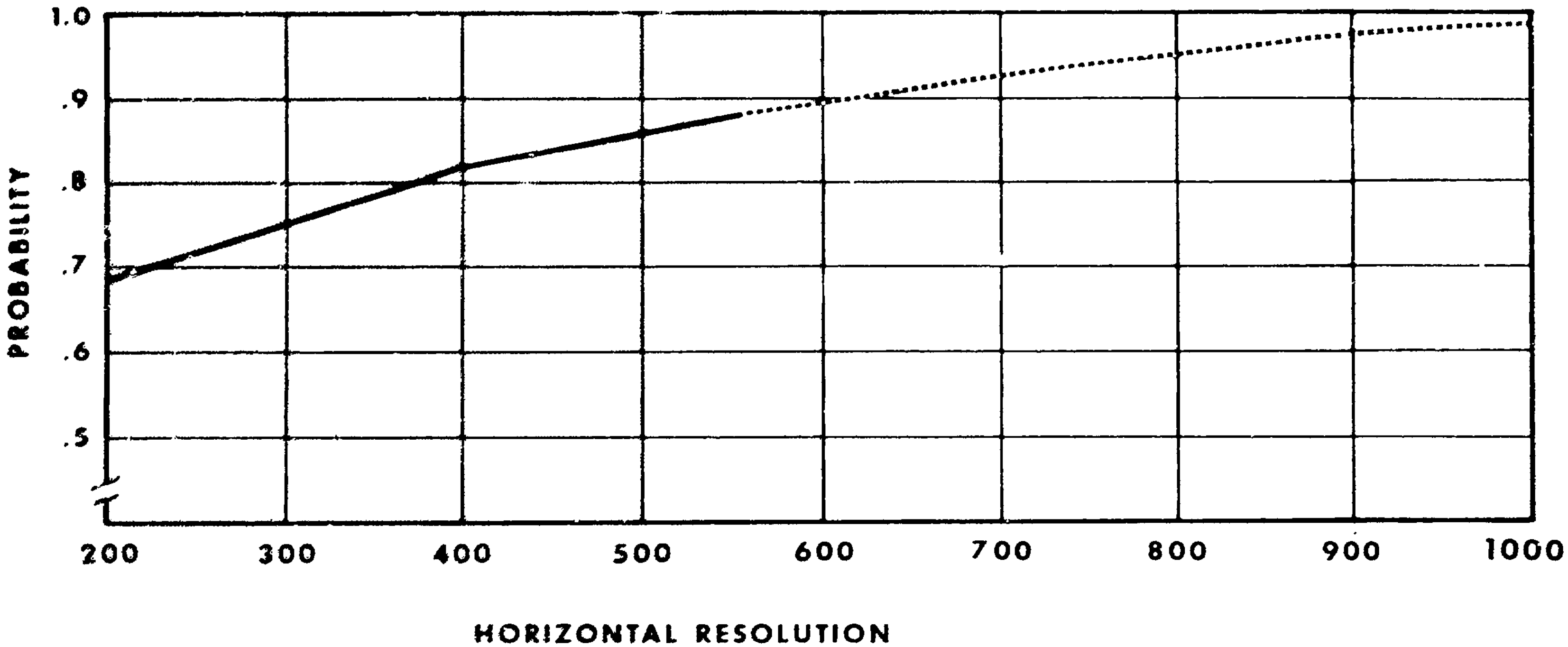


FIGURE 25 TARGET RECOGNITION PROBABILITY AS A FUNCTION OF RESOLUTION

probability of target detection increases as a function of resolution. Both curves begin to level off at approximately 900 TV lines.

The other consideration in determining the optimum number of scanning lines is the signal-to-noise ratio performance of the sensor system. An analysis was made of a high resolution vidicon sensor (RCA 23073) to determine the signal-to-noise ratio as a function of highlight illumination. The signal-to-noise ratio is given in reference 19 as follows:

$$\frac{S}{N} = \frac{I_s}{\left[4KTF\left(\frac{1}{R_1} + \frac{R_T}{R_1^2} + \frac{4\pi^2 C_1^2 F^2 R_T}{3} + 20(I_s + I_d)\right)\right]^{\frac{1}{2}}} \tag{1}$$

where:

- I_s = vidicon signal current = 4×10^{-7} amps
- I_d = vidicon dark current = 0.5×10^{-7} amps
- R_1 = input load resistor
- C_1 = total input shunt capacitance
- R_T = shot noise equivalent resistance of input
- F = system bandwidth
- K = Boltzmann constant
- T = absolute temperature

The results of the signal-to-noise ratio analysis are plotted in Figure 26 for a 525, 875, 945, and 1,023-line system with the bandwidth selected to give equal horizontal and vertical resolution values. This graph clearly shows that the useful range of light levels for a 1023-line system is much less (approximately one order of magnitude less) than for an 875-line system and the contrast performance is poorer (considerably lower) at all light levels. The resolution advantage of the 1023-line system over the 875-line system is at least partially offset by the poorer contrast capability of the 1023-line system. It is therefore felt that the 875 TV line system should still be competitive with the 1023 TV line system because of the advantages it offers in reduced bandwidth (12.9 MHz vs 19.5 MHz) and the reduced size and complexity of the memory required for the digital scan converter which has an impact on total system reliability.

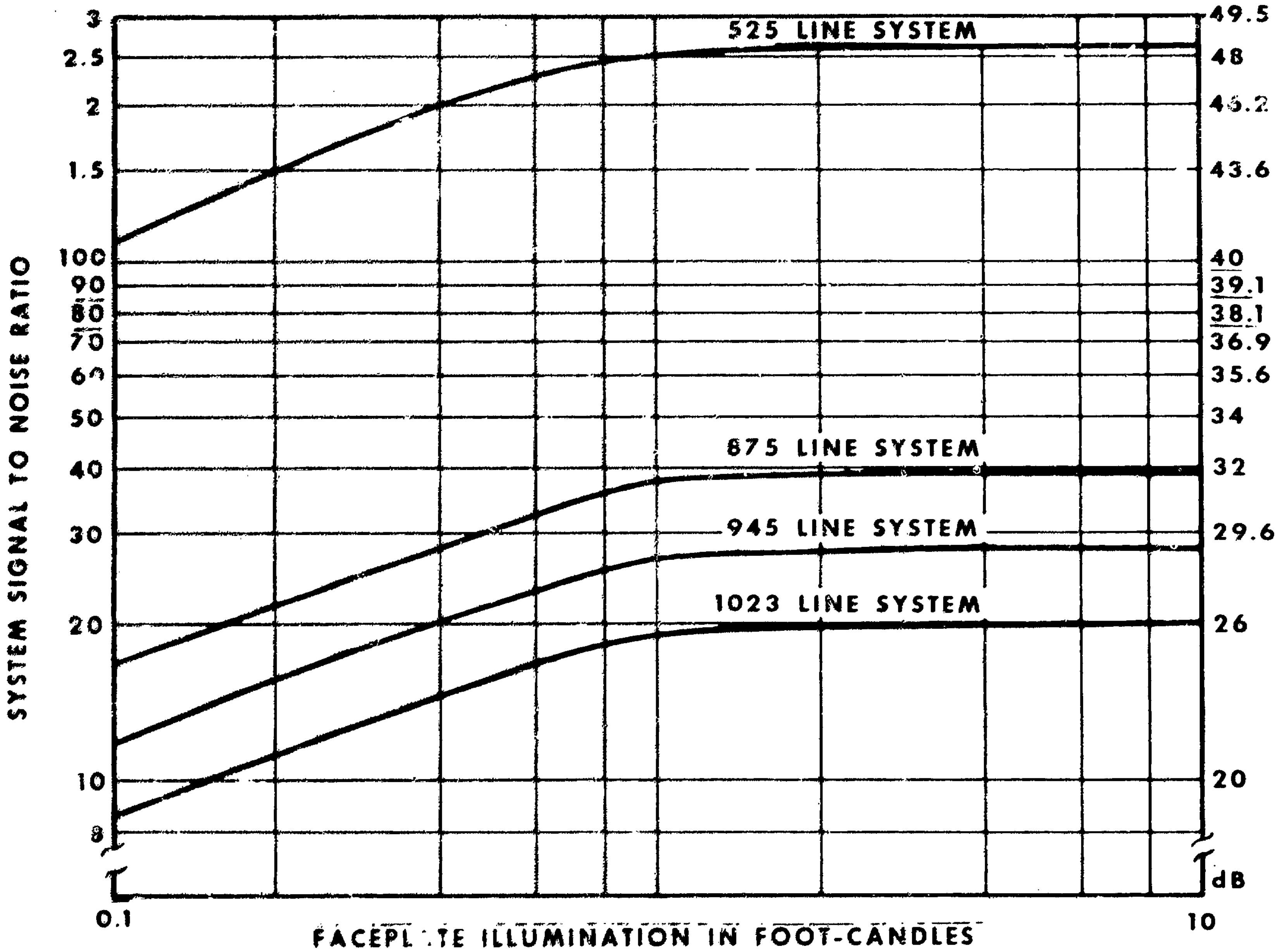


FIGURE 26 SIGNAL-TO-NOISE COMPARISON OF VIDEO SYSTEMS

The optimum design goal for a digitally addressed dot matrix display system is considered to be a 1023-line system with 946 active scanning lines using a 100 dots per inch matrix with a 5 mil spot diameter and a contrast ratio capability sufficiently high to permit imaging of 10 shades of gray. This results in a 9.46-inch square display format.

The first alternate design goal is for an 875-line system with 807 active lines using 100 dots per inch with a 5 mil spot diameter and a contrast ratio capable of providing 8 shades of gray. This results in an 8.07-inch square display format. The second alternate is for an 875-line system with 807 active lines using 80 dots per inch with a 6.25 mil spot diameter and a contrast ratio capable of providing 8 shades of gray. This results in a display format of 10.07 inches square.

2.3.4 Display Contrast and Brightness Requirements

The display contrast must be sufficiently high so as to permit imaging 8 to 10 shades of gray on the display screen in the presence of a 10,000 foot-Lambert ambient environment. This requires an approximate contrast ratio of 12 to 1 for 8 shades of gray and 23 to 1 for a 10 shades of gray capability.

The display contrast ratio can be calculated from the following expression.[18]

$$\text{Contrast Ratio (CR)} = \frac{B_{max}T + B_o(T_s^2 R + K)}{B_{min}T + B_o(T_s^2 R + K)} \qquad (2)$$

where:

B_{max} = highlight screen brightness

B_{min} = noise level

T = transmission of filter stack

T_s = transmission of circular polarizing filter with respect to specular light

K = front surface reflectance of dichroic coating

B_o = ambient illumination readout on display face

R = reflectance of display screen

Equation 2 was solved for display contrast ratios of 23 to 1 and 12 to 1 for a 10,000 fL ambient environment using a circular polarizing filter with a rejection ratio of 2.8×10^{-3} and a transmission of 0.35 with a front surface reflection of 2×10^{-3} and a display screen reflectance of 0.5. The results are plotted as curves 1 and 2 respectively in Figure 27. The highlight display brightness = 2,200 fL for the 23 to 1 contrast ratio for 10 shades of gray, and 1,100 fL for the 12 to 1 contrast ratio with 8 shades of gray. Both cases assume optimistic filter performance values and assume the use of a honeycomb filter in front of the display screen to limit off-axis rays incident on the screen to ±15°.

2.3.5 Symbology Size Requirements

The symbol size should be large enough to permit accurate and rapid character recognition and the character font should be fine enough to avoid structural detail. All moving symbology on the VDS formats will have a character height of 0.205 inch, which subtends an angle of approximately 24 arc-minutes at the normal viewing distance of 29 inches, and the character font will be 15x21 dots (width x height).

Figure 28[20] is a graph showing the general relation of symbol resolution to viewing distance. The VDS character height (0.205 inch) is shown at the normal 29 inch cockpit viewing distance, indicating that it is well within the normal operating region for good display design.

Figure 29[21] is a 4-dimensional plot of readout accuracy as a function of character size, blur, and contrast. The VDS character size (approximately 24 arc minutes at 29 inch viewing distance) is indicated on the graph. This curve shows that the accuracy is close to 100% performance. Figure 30 is an almost identical 4-dimensional plot except that the ordinate is speed of readout in characters per second instead of accuracy. The 24 minutes of arc character height suggested for the VDS is very close to the maximum possible performance at approximately 1.35 characters per second.

2.3.6 VDS Performance and Design Objectives

The following design objectives are based on the results of the systems performance analysis. An optimum design goal is specified along with a first

and second alternate design goal. The final selection will be based on the results of the preliminary system design analyses which will consider performance, system complexity, reliability, and cost effectiveness. These design and performance objectives can be used as a set of criteria against which the various dot matrix display techniques can be evaluated to determine their potential applicability for use in a 1985 era VDS.

TABLE 17 DOT MATRIX VDS PERFORMANCE AND DESIGN OBJECTIVES

	Design Goals	1st Alternate Design Goals	2nd Alternate Design Goals
1. Display Resolution (Spot Size)	0.005 in.	0.005 in.	0.00625 in.
2. Matrix Spacing (Dots/Inch)	100/in.	100/in.	80/in.
3. Scanning Standard Total Lines	1023	875	875
4. Number of Active Scanning Lines	946	807	807
5. Display Size (Active Area)	9.46 in.	8.07 in.	10.07 in.
6. Frame Rate with 2:1 Interlace	30/sec.	30/sec.	30/sec.
7. System Bandwidth	19.5 MHz	12.9 MHz	12.9 MHz
8. Gray Scale	10 shades	8 shades	8 shades
9. Contrast Ratio	23:1 min.	12:1 min.	12:1 min.
10. Screen Brightness	2200 fL	1100 fL	1100 fL
11. Symbol Size, Height x Width	0.205x0.145	0.205x0.145	0.20x0.150
12. Symbol Font	21x15	21x15	16x12

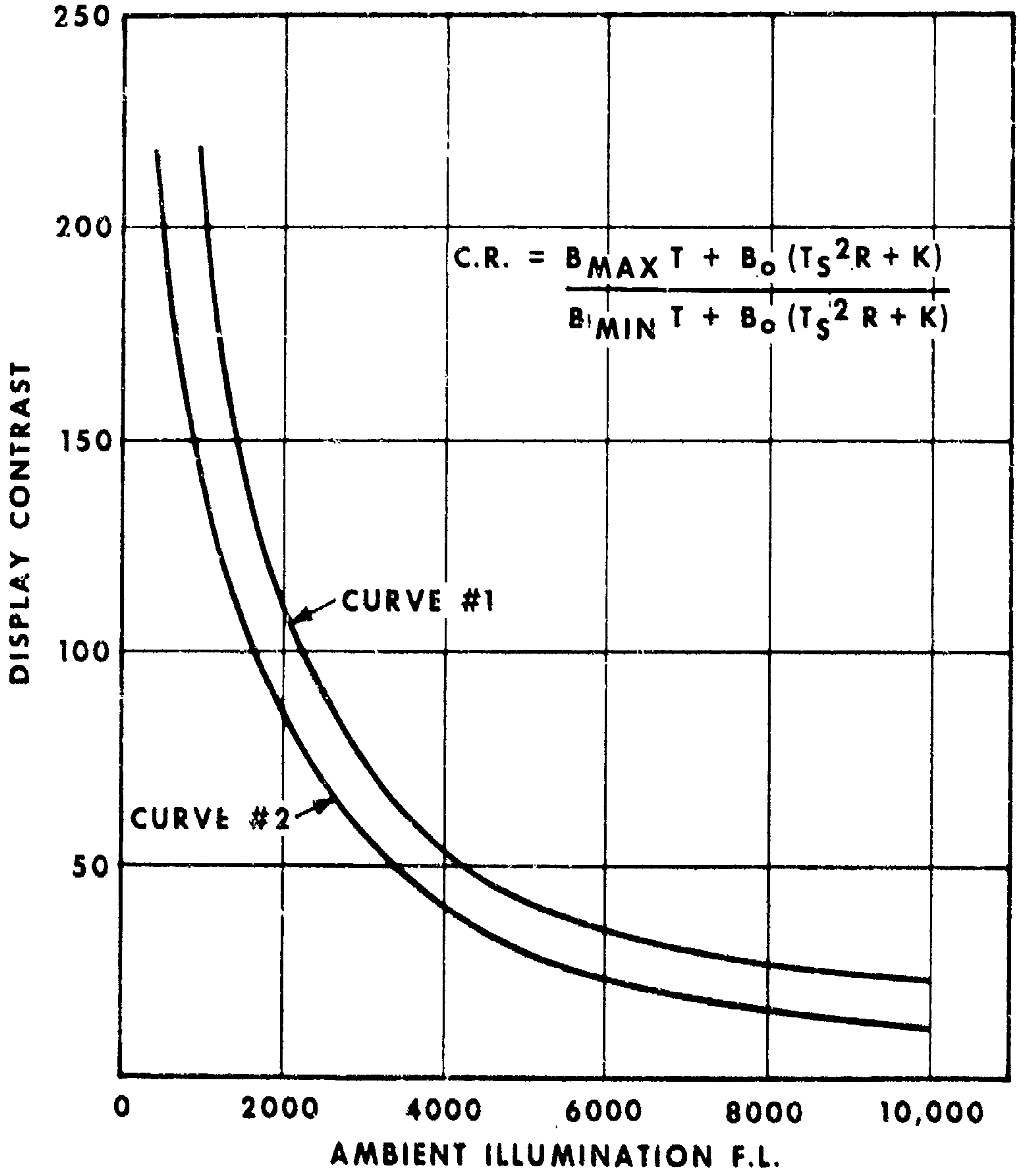


FIGURE 27 DISPLAY CONTRAST VS AMBIENT ILLUMINATION

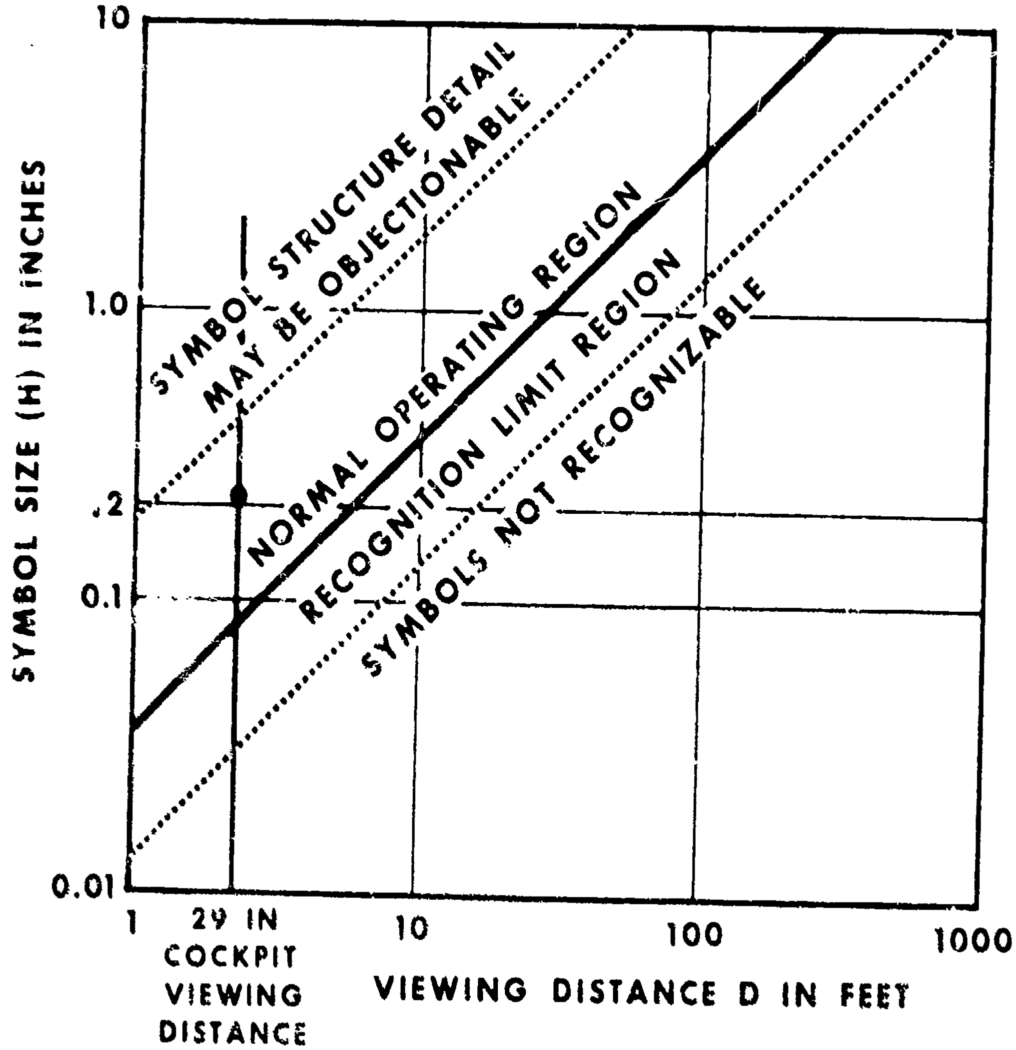


FIGURE 28 RELATION OF SYMBOL RESOLUTION TO VIEWING DISTANCE

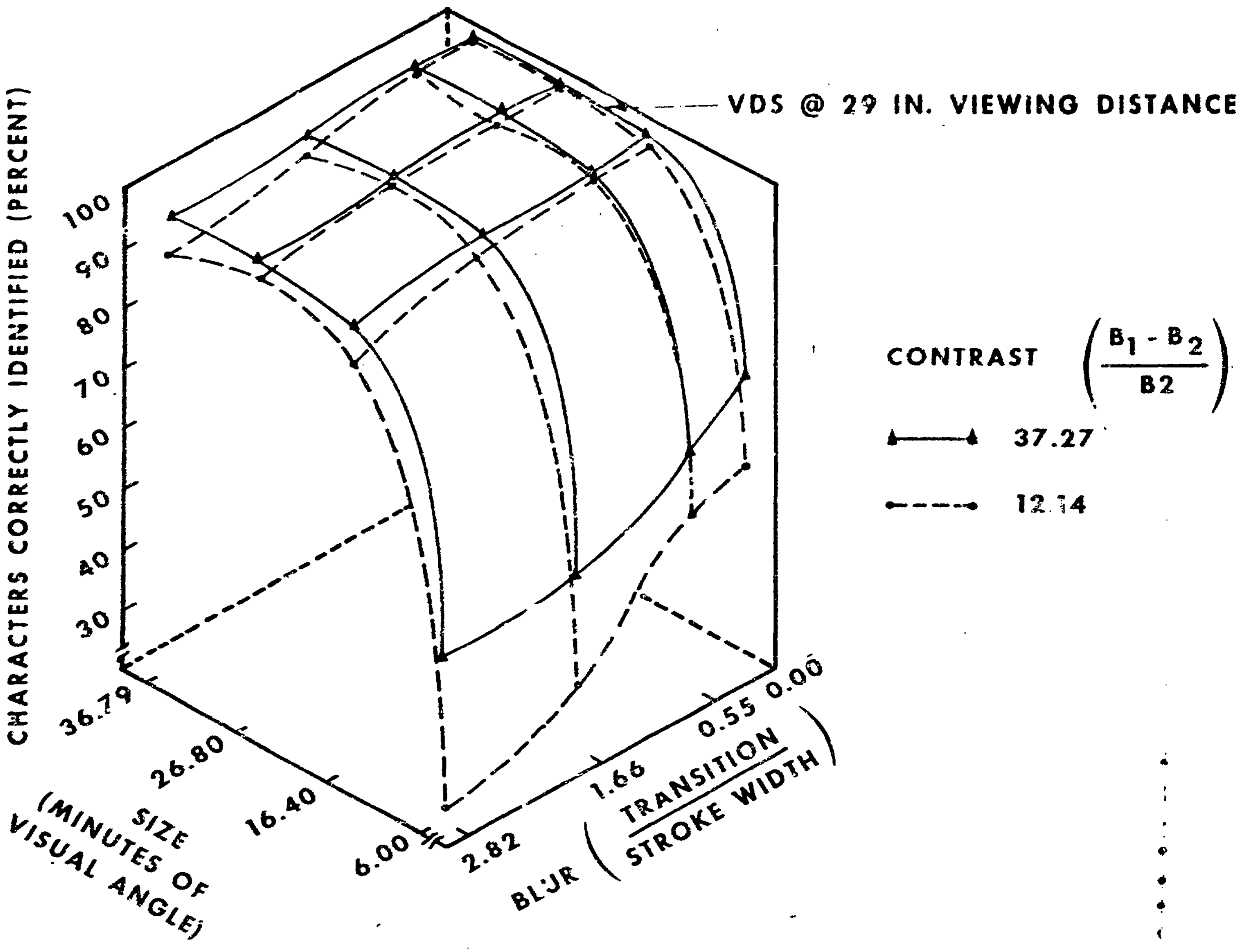


FIGURE 29 PERCENT OF CHARACTERS CORRECTLY IDENTIFIED VS SIZE, BLUR, AND CONTRAST OF LETTERS AND NUMBERS

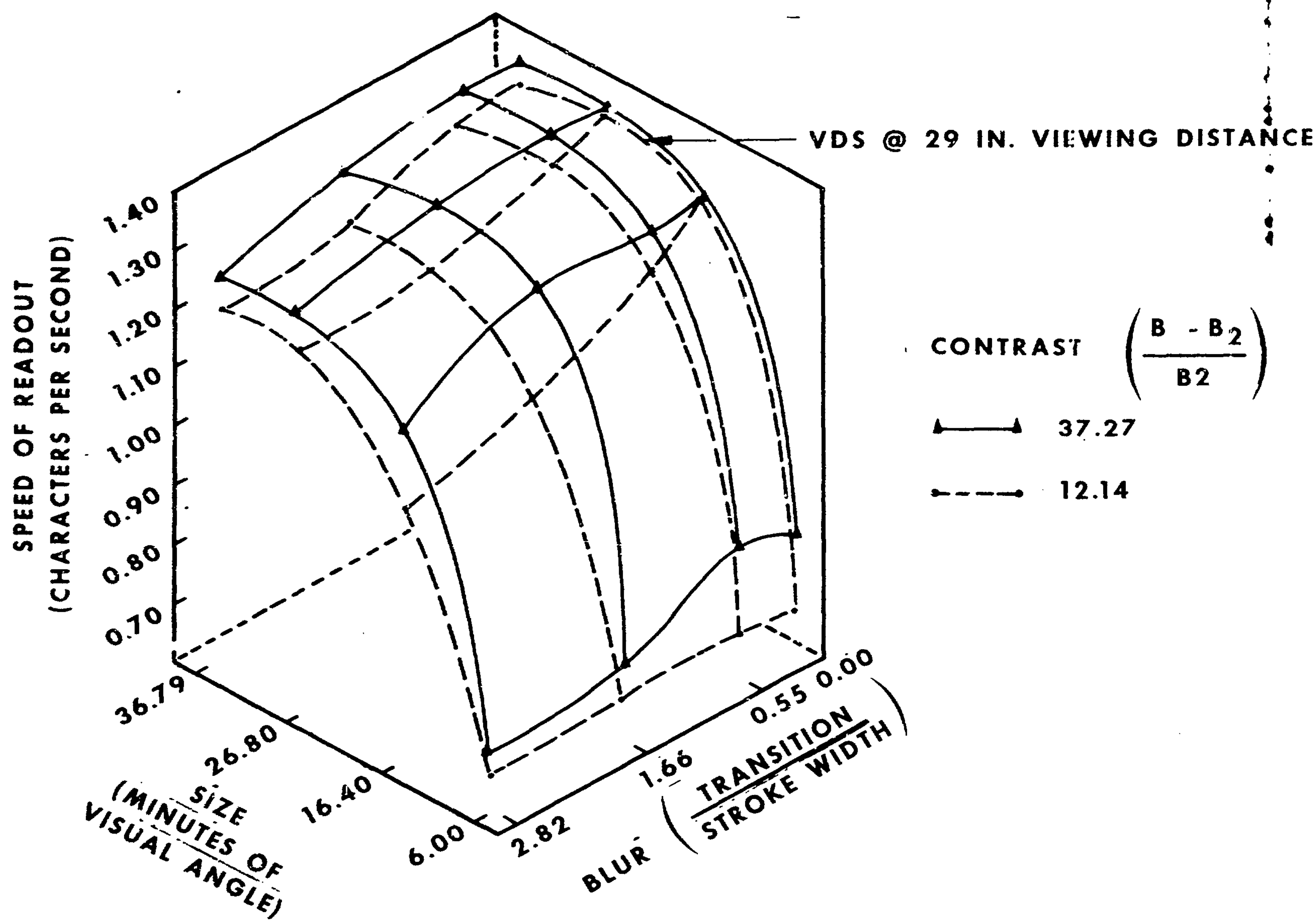


FIGURE 30 SPEED OF READOUT OF LETTERS AND NUMBERS VS SIZE, BLUR, AND CONTRAST

3.0 DERIVATION OF VDS DESIGN GOALS AND WEIGHTING FACTORS

This section will discuss the derivation of the vertical display system design goals and the formulation of an appropriate set of weighting factors to evaluate the performance capabilities of the non-CRT display techniques. The weighting factors will be used to select the most suitable VDS technique for a 1985 era naval all-weather attack aircraft.

3.1 VERTICAL DISPLAY SYSTEM PERFORMANCE CHARACTERISTICS AND DESIGN GOALS

The operational performance characteristics and design goals for a dot matrix type VDS to be used aboard a 1985 era naval all-weather attack aircraft were derived during the first part of the study and are listed in Table 3.1. The primary design goals require the use of a 1023 line scanning standard with a dot density of 100 dots per inch and 10 shades of gray. The first and second alternate design goals utilize an 875 line scanning standard with dot densities of 100 and 80 dots per inch respectively and 8 shades of gray. The design goal values for a screen brightness of 2500 foot-Lambert with 10 shades of gray and 1300 foot-Lambert with 8 shades of gray assume the use of a display output light source with a broad spectral emission (white light) and an efficient filter system. For the case of a display technique with a narrow spectral light output (monochromatic light) such as a laser or light emitting diode a much more efficient (bandpass) filter system can be used with a higher rejection ratio of incident sunlight. In this case it is estimated that the screen brightness requirement can be a factor of 4 times less than that required for the broad spectral output light source and still attain the same contrast and gray scale values.

3.2 DERIVATION OF WEIGHTING FACTORS FOR THE EVALUATION OF VDS CANDIDATE DISPLAY TECHNIQUES

A list of 24 of the most important display performance characteristics and operational parameters was formulated for the purpose of evaluating and comparing the capabilities and limitations of the non-CRT candidate display techniques regarding their potential application in the 1985 VDS. These characteristics were selected as a result of studies which indicated that they would have a direct effect on the video system performance and could be used

TABLE 3.1 DOT MATRIX VDS PERFORMANCE AND DESIGN OBJECTIVES

		Design Goals	1st Alternate Design Goals	2nd Alternate Design Goals
1.	Display Resolution (Spot Size)	0.005 in.	0.005 in.	0.00625 in.
2.	Matrix Spacing (Dots/Inch)	100/in.	100/in.	80/in.
3.	Scanning Standard Total Lines	1023	875	875
4.	Number of Active Scanning Lines	946	807	807
5.	Display Size (Active Area)	9.46 in.	8.07 in.	10.07 in.
6.	Frame Rate with 2:1 Interlace	30/sec.	30/sec.	30/sec.
.	System Bandwidth	19.5 MHz	12.9 MHz	12.9 MHz
8.	Gray Scale	10 shades	8 shades	8 shades
9.	Contrast Ratio	23:1 min.	12:1 min.	12:1 min.
10.	Screen Brightness	2500 fL	1300 fL	1300 fL
11.	Symbol Size, Height x Width	0.205x0.145	0.250x0.145	0.20x0.150
12.	Symbol Font	21x15	21x15	16x12

as a guide to the eventual determination of whether the candidate display techniques could achieve the level of performance required for an operational VDS. A minimum and maximum value was established for each characteristic, where appropriate, in order to define an acceptable range of values within which an assignment of points could be made. A set of additive weighting factors or points was assigned (by NADC representatives) to each of the 24 characteristics with a total value equal to 100 points. See Table 3.2. The weighting factors were assigned so that the maximum number of points were obtained if a particular technique met the design goals specified for the VDS and a lesser number for lower performance levels down to the minimum value of the acceptable range. The assignment of points within the acceptable range was on a linear basis. For some of the more important characteristics, such as brightness, uniformity, gray scale reliability, volume, weight, and power a negative weighting factor could also be applied with points subtracted up to the maximum number allocated for that particular display characteristic or parameter.

The assignment of the weighting factor points was made by NADC in a variable fashion in order to accentuate the value of the characteristics considered to be of most importance by the Navy for this application, and to emphasize the operational characteristics that determine if the display techniques could perform at the levels required by a 1985 VDS.

The Navy placed great emphasis on the characteristics associated with reliability (12 points) maintainability (5 points), ruggedness and environmental qualifications (8 points) which collectively amounted to 25% of the total 100 points. Two of the display characteristics (production feasibility and design complexity) had no limit established for the acceptable range, so that the evaluation could assign from 0 to 5 points depending on the degree of design complexity and the number of production problems anticipated for each display technique.

TABLE 3.2 - VDS PERFORMANCE CHARACTERISTICS WEIGHTING FACTOR

		VDS DESIGN GOAL	ACCEPTABLE RANGE	WF	POINTS FOR PERFORMANCE
1.	RESOLUTION	100 DOTS/INCH	60 - 100+ dots/inch	5	60 DOTS = 1; 100 DOTS = 5
2.	SPOT SIZE	5 MILS	5 - 8 MILS	3	8 MILS = 0.6; 5 MILS = 3
3.	SCREEN SIZE (NUMBER OF ELEMENTS)	10 IN. SQUARE 10^6 ELEMENTS	5 IN. - 10 IN.	4	10 IN. 10^6 ELEMENTS = 4 5 IN. 2.5×10^5 ELEM. = 2
4.	BRIGHTNESS	1300 FL minimum	500 - 2500 FL	7	500 FL = 0, 2500 = 7 100 = -7
5.	UNIFORMITY	±10%	±10% - ±18%	5	±10% = 5; ±20% = 0; ±30% = -5
6.	CONTRAST RATIO	23 - 1	8 - 1 TO 30 - 1	2	8 - 1 = 0.5; 23 - 1 = 2
7.	GRAY SCALE	10 SHADES	7 - 12 SHADES	8	10 Shades = 8 6 SHADES = 0 2 SHADES = -8
8.	COLOR	2 OR MORE COLORS	R, G, B, W	1	1 COLOR = 0; DUAL COLOR = 1
9.	SCANNING RATES	20 MHz	12 - 20 MHz BW	12	20 MHz = 12; 5 MHz = 3
10.	STORAGE	MHz	15 SEC. - 10 MIN.	1	WITH STORAGE = 1; WITHOUT STORAGE = 0
11.	RELIABILITY MTBF	2000 HRS. TOTAL SYSTEM 5000 HRS. DISP. & ELEC.	MTBF: 1000 - 5000 HRS.	12	1000 HRS. = 2; 5000 HRS. = 12; 300 HRS. = -12
12.	MAINTAINABILITY	1000 HRS.	MEETS MIL-STD-454	5	200 HRS. = 1; 1000 HRS. = 5
	RUGGEDNESS & ENVIRONMENTAL LIMITATIONS (ITEMS 13 - 17)	RUGGEDNESS MEETS MIL-E-5400			

TABLE 3.2 - VDS PERFORMANCE CHARACTERISTICS WEIGHTING FACTOR (CONT'D)

		VDS DESIGN GOAL	ACCEPTABLE RANGE	WF	POINTS FOR PERFORMANCE
13.	TEMPERATURE & HUMIDITY	-54°C TO +71°C	MEETS MIL-E-5400M	2	TEMP. -54°C TO +71°C CONTINUOUS OPERATING
14.	SHOCK	15 g FOR 11 MSEC	MEETS MIL-E-5400M	2	SHOCK 15g FOR 11 MILLI-SECONDS NON-OPERATING
15.	VIBRATION AND ACCELERATION	±10 g 70-500 CPS	MEETS MIL-E-5400M	2	VIBRATION ±10 g
16.	EMI AND RFI		MEETS MIL-STD 461	2	EMI REJECTION OF UNDESIRED SIGNALS - 30 - 106 Hz, RFI - 10 KHz - 400 MHz, 10 V/M SHELTERED
17.	VOLUME	$<$0.5 FT^3	0.5 - 2.5 FT^3	4	0.5 FT^3 = 4; 2.5 FT^3 = 0; 4 FT^3 = 4
18.	FORM FACTOR	2 PACKAGES	1 - 3 PACKAGES	1	SEPARABLE INTO 2 OR MORE PACKAGES = 1; ONE PACKAGE = 0
19.	WEIGHT	$<$50 POUNDS	$<$230 POUNDS	3	230 lbs. = -3, 140 lbs. = 0; 50 lbs. = 3
20.	AVERAGE POWER CONSUMPTION	$<$100 WATTS	$<$300 WATTS	3	100 WATTS = 3 350 WATTS = 0 600 WATTS = -3
21.	PEAK POWER CONSUMPTION		$<$1000 WATTS	1	$<$1 KW = 1; $>$1 KW = 0
22.	PRODUCTION FEASIBILITY	EASILY PRODUCED PRESENT TECHNOLOGY		5	VARIABLE
23.	DESIGN COMPLEXITY	LOW COMPLEXITY		5	VARIABLE
24.	PRODUCTION COST	LOW COST ($<$ \$25K)	25K - 125K	5	25K = 5; 50K = 4; 75K = 3; 100K = 2; 125K = 1

[illegible]

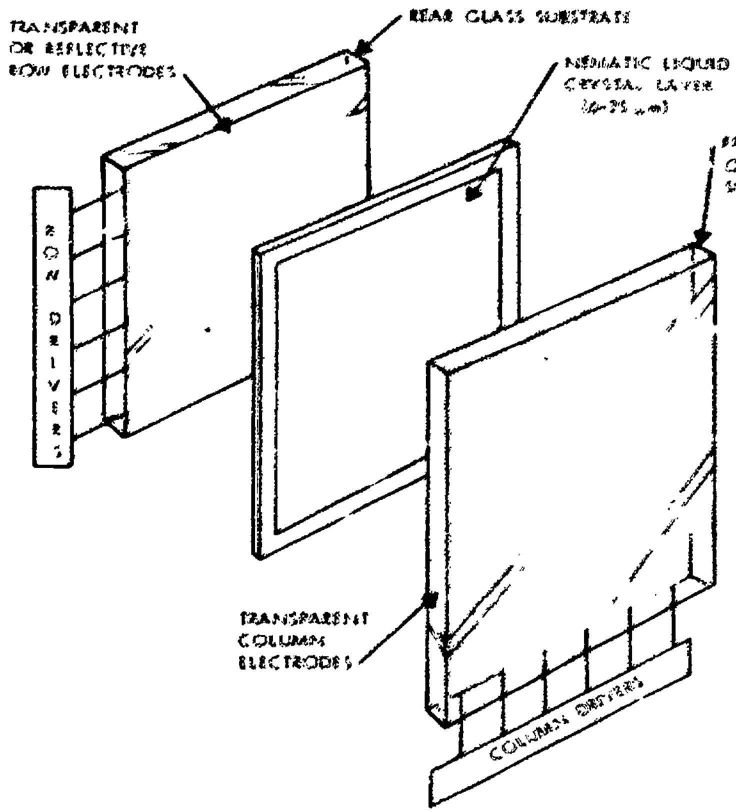
This section reviews [illegible] technology [illegible] display techniques that are considered as possible solutions for the [illegible] applications. The techniques include the following [illegible] light valves, which include liquid crystal, ferroelectric, and magneto-optic display techniques, electron beam addressed light valves, [illegible] film, cathodochromic and [illegible] techniques. [illegible] light emitting diodes, electroluminescent [illegible], and [illegible]

[illegible] LIGHT VALVE DISPLAY TECHNIQUES

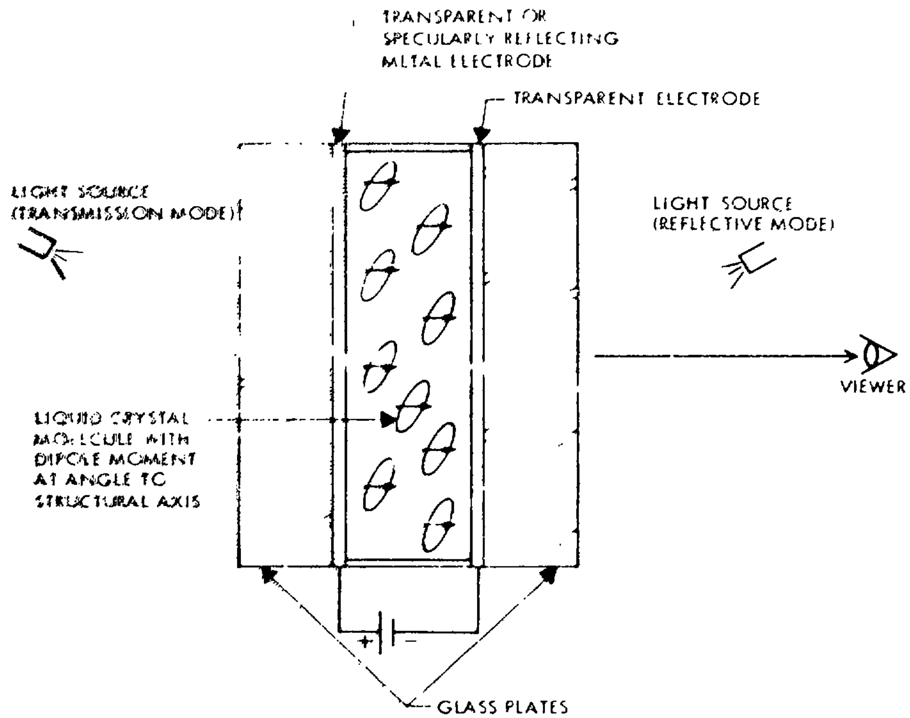
In a light valve display technique, the display device generates no optical radiation of its own but instead modulates the transmission or reflection of light from an external source of illumination to provide a visual display image for the viewer. The three light valve techniques discussed in this section - liquid crystals, ferroelectric ceramics, and magneto-optic films - are all flat panel displays which are addressed by an X-Y matrix of conductors. The simultaneous application of voltages to a particular X or row conductor and a particular Y or column conductor activates the intervening material in the region where they cross. The coincident area at the crossing point constitutes one resolution element. A brief description of each display technique is presented with a discussion of its more important operational and performance characteristics.

[illegible] Liquid Crystal Display

The most common liquid crystal display technique utilizes the dynamic scattering property of the nematic liquid crystal phase. The display panel shown in figure 31 is relatively simple to construct and consists of a very thin nematic liquid crystal layer (1/4 to 1 mil thick) sandwiched between two glass substrates. Transparent thin film electrodes are deposited on the inner surfaces of the glass plates and the sandwich structure is hermetically sealed. The simultaneous application of voltages to X and Y electrode produce an electric field across one resolution element. In nematic crystals having a



a. Panel Configuration



b. One Resolution Element

A2-0087 1A

FIGURE 31 DYNAMIC SCATTERING LIQUID CRYSTAL DISPLAY

negative dielectric anisotropy, the electric dipole moment of the molecule has a larger component perpendicular to the molecular axis than parallel to it. When the dipoles attempt to line up parallel to the applied field, as seen in figure 31 , the molecular axes are then aligned almost perpendicular to the field. Under the influence of the electric field, ions generated near the cathode begin to move through the crystal toward the anode. The interaction of these charge carriers with the aligned molecules results in shear forces and turbulence which in turn produce localized variations in the index of refraction and cause incident light to be dynamically scattered.

The display can be viewed in the transmissive or reflective mode. In the transmissive mode, the light source is placed behind the panel at an angle appropriate for nondirect viewing. (Direct viewing would result in higher brightness but lower contrast.) A nonaddressed resolution element is transparent. Collimated light passes through the transparent electrodes and liquid crystal cell at an angle to the observer and, therefore, the element appears dark. When voltage is applied, the turbulence condition within the element causes light to be scattered in the direction of the viewer and the element appears bright. The relative brightness or gray level depends on the amplitude of the applied voltage.

In the reflective mode, the light source is in front of the panel and the back electrodes are of a specularly reflecting metal. When a resolution element is addressed and goes into the dynamic scattering mode, incident light scattered within the element and reflected from the back electrode causes the element to appear bright to the observer. Light striking a nonaddressed and thus transparent element is specularly reflected from the back electrode at an angle equal to the angle of incidence causing this element to appear dark to the viewer. The relative brightness of the ON element is again a function of the applied voltage and resultant scattering intensity.

In dynamic scattering by conduction-induced turbulence the turnoff or decay times are relatively long, 100 to 200 msec. Shortened turnoff times (< 5 msec) can be achieved by oscillating domains of liquid crystal molecules through the

use of ac excitation in a critical frequency range. In both cases, the ON element becomes milky white; however, the scattering and hence the contrast obtained in the oscillating mode is less than that produced by the intense turbulence of the dynamic scattering mode.

The major characteristics of the liquid crystal matrix display are itemized and discussed below.

- <u>Panel Fabrication</u> - The basic construction of the panel is fairly simple - a thin layer of liquid crystal sandwiched and sealed between two electroded glass plates. The result is a low cost, relatively rugged flat panel that can be built in a wide range of sizes and shapes and is amenable to batch fabrication.

- <u>Resolution</u> - The resolution or number of elements per inch is limited mainly by the electrode deposition. It is not unreasonable to anticipate liquid crystal displays with resolutions of 100 to 500 elements per inch. The spot size is also a function of electroding and is equal to the coincident area of the X and Y electrodes at the crosspoint.

- <u>Brightness</u> - High brightness values can be achieved since the display is not a light generator, but depends on an external light source for illumination. Display brightness then is limited mainly by the intensity of the source.

- <u>Contrast</u> - Good contrast ratios (ratio of the brightness of an activated to a nonactivated element) have been achieved, sufficient to obtain over eight gray shades (~12 brightness levels). These contrast ratios have been obtained by doping the pure nematic liquid crystal to lower its resistivity. The improved conductivity increases the dynamic scattering and also shortens the response time of the crystal. The disadvantages incurred, however, are a subsequent narrowing of the nematic phase temperature range due to the dopant and a higher power consumption within the panel due to the higher conductivity of the crystal.

One of the major problems in cockpit display applications is the loss of contrast or "washing out" of the display under high ambient illumination conditions. Although the transmissive viewing mode has been found to be

more pleasing to the eye, the obvious advantage of operating the liquid crystal display in the reflective mode is the increase in display contrast as the ambient light level increases. Note that the contrast changes with viewing angle so that the optimum viewing angle will depend on the position of the light source relative to the display.

- Color - Addition of a pleochroic dye to some types of nematic liquid crystal can be used to obtain a multicolor display. Pleochroic dye molecules will absorb plane-polarized light when they are oriented in a particular direction with respect to the plane of polarization. Since the "guest" dye molecules are forced to line up in the same direction as the "host" liquid crystal molecules when an electric field is applied, a variation in the color of transmitted light can be achieved by an appropriate variation in the applied voltage across each cell.

- Storage - Mixtures of nematic and cholesteric crystals also exhibit a dynamic scattering effect due to turbulence produced by the migration of ions under the influence of an applied electric field. The light scattering centers, which consist of interfaces between the two kinds of material, will remain for a period of hours or even weeks after the field has been removed. The molecules can be reordered by an audio frequency voltage waveform.

- Environmental Limitations - Liquid crystals currently available have limited temperature ranges and are sensitive to stray fields, mechanical stress, impurities, etc. Many liquid crystals become crystalline solids near room temperature; however, a combination of the two most commonly used crystals, MBBA and EBBA, has a temperature range extending from about -10 to 50°C. With ruggedization, shielding and operation in a temperature-controlled environment, the liquid crystal display should be a high-reliability device.

- Lifetime - One of the major problems with liquid crystal displays has been short life. The commonly used Schiff-base materials, such as MBBA and EBBA, are compounds that hydrolyze in the presence of moisture, acids and bases so that great care must be taken during assembly of the panel before sealing. These compounds also suffer some decomposition under ultraviolet

irradiation. In order to avoid the decomposition of the Schiff compounds, which occurs at the carbon-to-nitrogen double bond, another class of compounds is being investigated that uses carbon-to-carbon double bonds and is more resistant to deterioration. Another possible source of performance degradation is the use of a dopant which increases the contrast and shortens the response time of the liquid crystal but also increases the possibility of adding impurities to the crystal.

In addition to fabrication related sources of deterioration, there are operational sources such as ion depletion which cause a gradual reduction in contrast. The differential nature of the photochemical and electrochemical deterioration over the display area results in nonuniformities in brightness, response time, etc. Tests have shown that dc driven liquid crystal cells can have lifetimes of 1000 hours or less, primarily due to ion depletion. Operation using ac voltage waveforms will extend the panel lifetime to 10,000 hours. A value of 50,000 hours for ac operation appears feasible in the future.

- Switching Voltage - The dynamic scattering threshold voltage for a 0.5 mil thick nematic crystal layer is about 7 to 8 volts. As the voltage is increased, the intensity of scattering and the associated contrast ratio increase until a saturation point is reached (20 to 40 volts depending on the crystal type and thickness). The low operating voltages permit the use of integrated circuitry so that ultimately the addressing circuitry could be constructed on the backplate of the liquid crystal sandwich.

- Power - The major portion of the power will be dissipated in the driver circuits rather than within the display panel itself due to the rapid charging and discharging required of the display element capacitances and stray bus bar capacitances, particularly at high update rates. In general, however, power requirements are very low even when operating at high scanning rates or using high frequency voltages to shorten the element decay time.

- Threshold Problem - The nematic liquid crystal does not have the threshold characteristics required for a good operation in a matrix-addressed display system. While the full voltage is applied to the ON element, all other

elements along the row and column electrodes are subjected to a disturb pulse. The lack of a sharp threshold permits these elements to be partially activated. Shunting in the matrix sends part of the voltage to surrounding display elements which also go into the dynamic scattering mode and cause cross talk or lack of contrast. Some of the schemes considered to eliminate these problems include the following:

1) The use of an appropriately biased diode at each resolution element to provide a threshold. All diodes would be biased off except those coincidentally selected by row and column signals (RCA).

2) The use of a ferroelectric ceramic layer in contact with the liquid crystal layer. When an ac voltage is applied to the double layer, the voltage effectively encounters a nonlinear and a linear capacitance in series. By suitably adjusting the capacitances, the voltage can be made to rise very rapidly across the crystal layer as compared with the total voltage across the sandwich. In this manner, the voltage at adjacent elements is well below the level required for activation. The polarization characteristics of the ceramic material can be used to achieve storage capability. (Siemens AG)

3) The application of two-frequency coincidence addressing which takes advantage of the different responses of certain nematic crystals to electrical signals of different frequencies. By simultaneously applying ac voltage waveforms to an X and Y electrode, one above the dynamic scattering frequency range and the other below it, the addressed element at which the two frequencies coincided would be OFF. The elements where the two frequencies did not coincide could be turned ON. Present disadvantages to this technique are several scanning cycles required to reach peak response and higher voltages (~50 volts) to get adequate response times and contrast ratios. (GE)

o <u>Scanning Rate</u> - The major problem in developing a liquid crystal display capable of presenting video information at 30 frames per second is the slow rise and decay time. The rise time (time required to reach 90 percent of peak scattering measured from the instant the excitation voltage is applied) and the decay time (time required to drop to 10 percent of

peak scattering measured from the instant the excitation voltage is removed) are both functions of the liquid crystal material, its thickness, temperature, conductivity, and the amplitude and frequency of the applied voltage waveforms. Typical nematic liquid crystal cells have rise times of 1 to 10 milliseconds and natural decay times of 20 to 1000 milliseconds following excitation by dc or low frequency ac current.

In order to operate at 30 frames per second, each liquid crystal cell must be addressed, must rise to the required dynamic scattering level, and must decay, all within 33 milliseconds or less. A one millisecond rise time can be obtained using a very thin layer of a nematic crystal having the appropriate resistivity. The decay time, however, even when operated above room temperature, is still marginal and sufficient to produce smearing. Two techniques can be used to reduce the decay time to less than 10 milliseconds. The first requires the application of a high amplitude voltage pulse (~200 volts) about 5 msec <u>after</u> the excitation voltage has been removed. By this time, the ions which had been migrating under the influence of the electric field have been neutralized and the high voltage pulse forces the dipole moments to realign themselves parallel to the direction of the field. The second scheme also quenches the decay time by removing the turbulence conditions, but does so with the application of an ac voltage waveform (10 to 40 kHz) <u>during</u> the 5 msec after the excitation voltage has been removed.

Assuming then that the rise and decay times can be adequately controlled, the problem of addressing each element and maintaining the required voltage across each element for the full 1 msec rise time remains. If a 1000x1000 element display were addressed a line at a time, a frame time of 1000 lines x 1 msec/line = 1 second would be required. This system would also require 1000 drivers to simultaneously modulate the 1000 elements per line. Obviously, some technique must be used to maintain the voltage across the element after it is addressed, thereby enabling all of the one million elements to be written in a 1/30 second frame time (~30 μsec per line or .03 μsec per element). Several such schemes are described in Reference 1 for both dc and ac excitation of a liquid crystal matrix display. One of the simpler dc schemes has two diodes and one capacitor

associated with each resolution element as reproduced in figure 32 . When a particular element is addressed by applying voltages to the appropriate X and Y electrodes, the reverse bias of the "set" diode D_1 is exceeded and a voltage is produced across the liquid crystal element and the capacitor which are in parallel. The capacitor maintains the charge for the rise time interval or until the end of the frame at which time the reverse-biased diode D_2 is forward-biased, thereby completely discharging both the liquid crystal element and the capacitor. Thus, diode D_1 provides an adequate threshold for matrix selection while the combination of capacitor C and diode D_2 maintains the addressing voltage across the element up to a full frame time, permitting lower excitation voltages and higher average brightness. Isolating devices other than diodes are also considered such as field effect transistors and gas discharge cells.

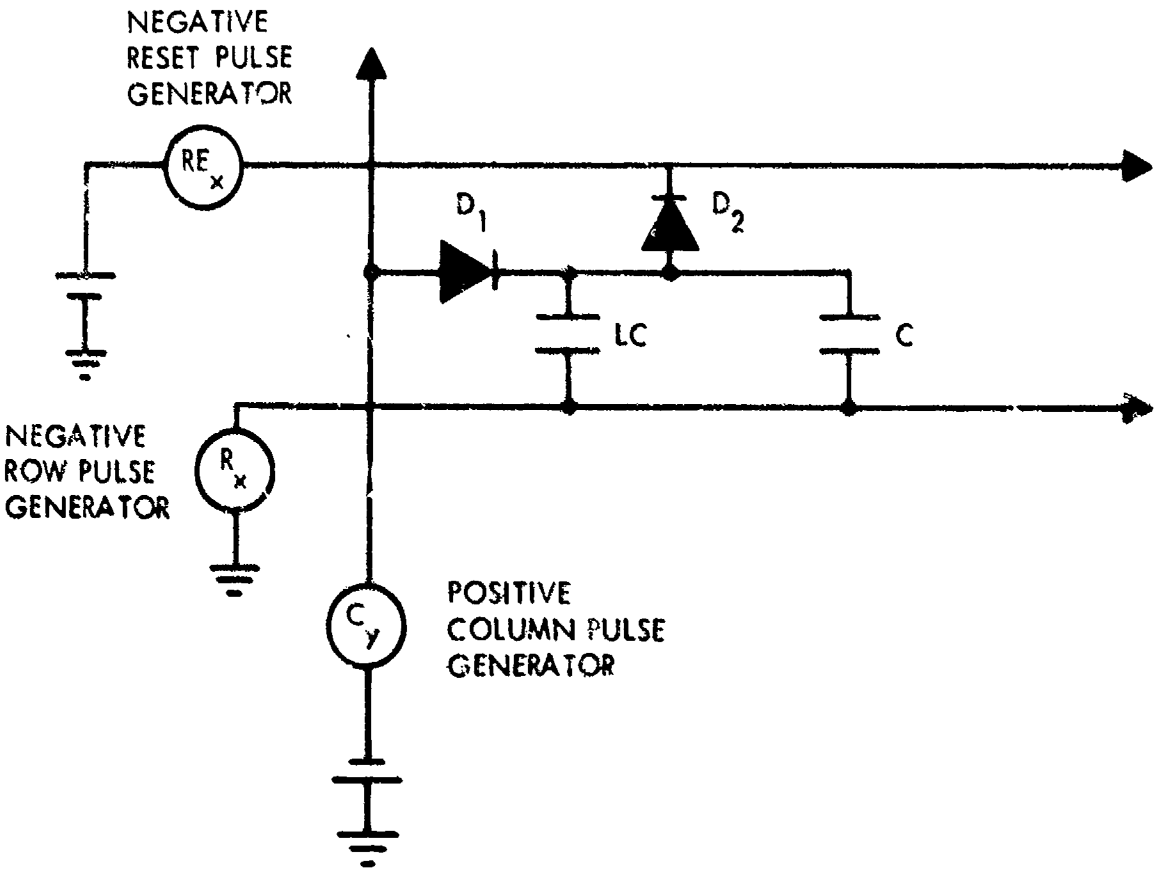


FIGURE 32 ADDRESSING CIRCUIT FOR ONE LIQUID CRYSTAL ELEMENT

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The use of such techniques will not only enable the display to operate at video rates, but may also reduce the number of required drivers from 1000 for a line-at-a-time addressing (30 μsec per line and therefore 30 μsec per element) to as few as 10 drivers for 10 elements-at-a-time addressing (30 μsec per line and only 0.3 μsec per element). The reduction in drivers and the corresponding reduction in circuitry would enhance the system reliability.

4.1.1.1 <u>Summary</u>

The liquid crystal display is one of the most promising techniques for satisfying the performance requirements of the vertical display system. Its major advantages are low voltage, low power and low cost, electrical compatibility with MOS driver circuitry, high resolution, high brightness and good contrast even in direct sunlight. The main disadvantages are half select and cross talk problems, slow response and decay times, complex addressing circuitry, limited temperature range, differential aging and high sensitivity to fabrication tolerances.

The ultimate feasibility of the liquid crystal display for the VDS application will depend on the development of an adequate scanning or multiplexing scheme to address the display matrix. The requirement of one or more circuit elements for each resolution element in the display, in order to provide an adequate threshold and to scan at video rates, will necessitate the use of integrated circuitry and mass-fabrication techniques. The eventual solution will probably be a silicon substrate as the backplate of the liquid crystal sandwich with the circuitry, including the modulators, formed by advanced semiconductor technology on the chip. In the case of a 10 inch by 10 inch matrix display, a modulator structure could be constructed consisting of perhaps 100 integrated submatrices, each on a 1 inch by 1 inch silicon chip backplate. Additional complexities would be encountered in the assembly and interconnection of the submatrices to prevent damage to the circuitry and to maintain linearity.

Should methods of fully integrated circuitry fabrication be developed for addressing large size, moderate resolution panels and should the device be ruggedized and operated in a temperature-controlled environment, the liquid crystal

matrix display will acquire the performance characteristics and reliability requirements for the VDS application.

4.1.2 Ferroelectric Ceramic Displays

Ferroelectric materials have two basic properties which enable them to be used as electrically controlled light valves: 1) Thin optically polished plates of certain fine grain ceramics which have been properly doped exhibit a high transmission of optical radiation; and 2) Polycrystalline ferroelectric ceramics can be given lasting polar characteristics by the application of a dc electric field for a short time in a process called poling. In the depoled state, the ferroelectric domains are randomly oriented. The application of a dc poling field causes the domains to orient themselves in a direction favorable with respect to the field, resulting in a spontaneous dipole moment. Reversal of the field polarity causes the domains to be reoriented, thereby shifting the spontaneous polarization vector. The ferroelectric domains and their field-induced motion can be observed visually when the crystals are suitably oriented between two crossed polarizers.

Figure 22 illustrates the operation of a bismuth titanate display under development at RCA Laboratories and Princeton Materials Science. A nine-resolution element display is shown in which the letter "T" has been written. To take advantage of the two optically distinguishable states which occur when the c-axis component of the polarization vector is tilted, the display is fabricated with the c-axis of the monoclinic crystal perpendicular to the incident illumination. Each line of resolution elements is then constructed from a thin bar of the bismuth titanate. A common row electrode is deposited along the bottom face of each bar. The individual resolution elements are formed by individual electrodes on the top surface of the bar with the elements in each column connected by a common conductor. Matrix addressing of a particular element is achieved by coincident pulses to the appropriate row and column leads.

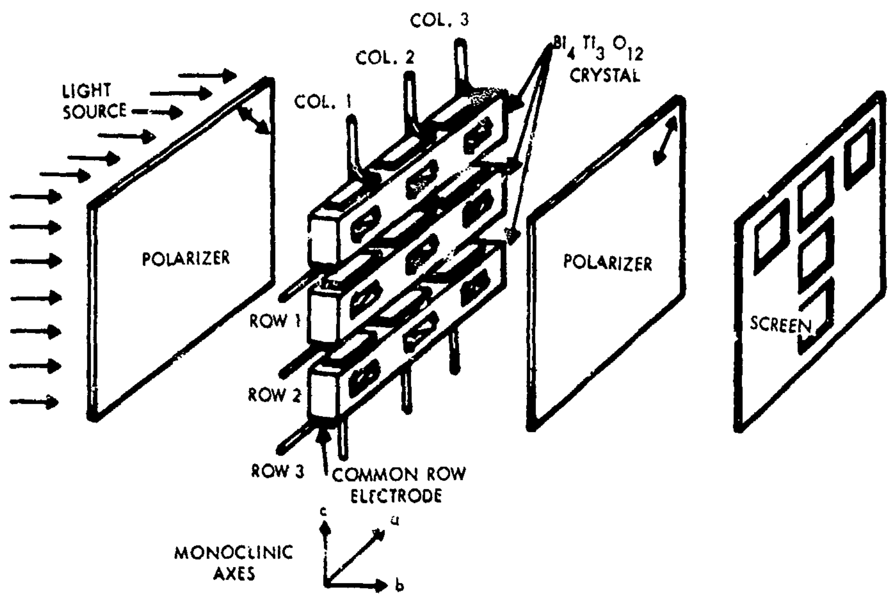
The electric field is applied in a direction transverse to the direction of the illuminating light and orients the polarization vector as shown, for example, in column 1, row 3 of figure 33. (The arrows shown within each of

the nine resolution elements on the bars represent the direction of the induced polarization vector and its components in the a- and c-axis directions.) With the polarizer oriented as shown, only light plane polarized in the indicated direction will be incident on the bismuth titanate structure. The analyzer is then set for extinction, no light is transmitted to the screen and the element is considered to be in an OFF state. Electrical switching of the electrodes causes a small rocking of the spontaneous polarization vector (~10 degrees) to a direction as shown in column 1, row 1. The extinction angle, however, changes by about 40 degrees, and light is then transmitted through the analyzer resulting in an ON element. The polarization directions shown in the nine-element display are those required to compose an optical "T" pattern.

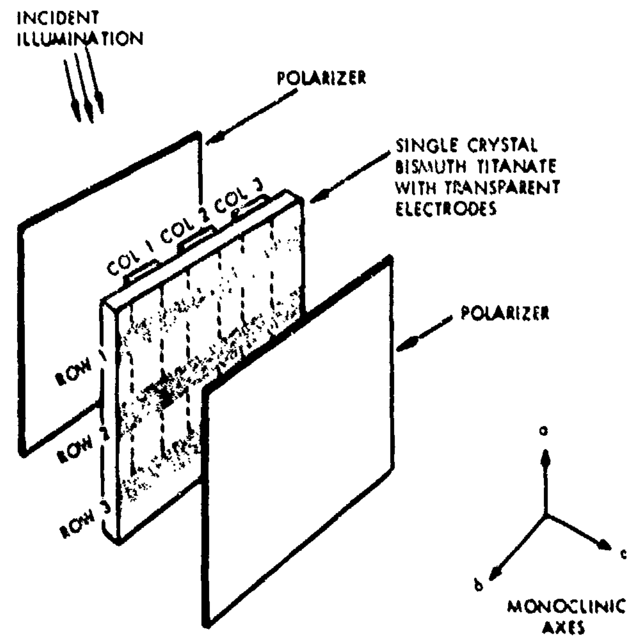
The ferroelectric ceramic display could be fabricated as a single crystal as shown in figure 33[(2)] The c-axis of the crystal is now directed perpendicular to the polarizers rather than parallel to them. The electrical switching is accomplished by transparent row and column electrodes on the a b surfaces. The crystal is mounted between crossed polarizers and tilted at an angle to the incident light. This technique reduces the fabrication complexity but also degrades the optical performance due to a decrease in light transmission and a rapid change in contrast ratio with viewing angle.

- <u>Panel Fabrication</u> - Crystals must be prepared in the form of long, highly polished bars. Present growth and processing techniques must be improved to yield large, high-quality twin-free crystals. The b and c dimensions must be very thin to obtain optimum optical performance at reasonable operating voltages and must maintain close tolerances to obtain good electrical and optical uniformity. A large number of bars must then be stacked together and insulated from each other to obtain an adequate size display (1000 bars for a 1000-line display). The assembly and interconnection of the bars into a matrix will present difficulties in maintaining linearity and preventing damage to the electroding and circuitry.

- <u>Resolution</u> - The resolution is limited by the c dimension of the crystal and the spacing required between the element electrodes along the bar. Reference 2 indicates that if c is the height of the element, the spacing between adjacent elements in a row must be 0.1 c to prevent arcing and



a. MULTI-BAR TECHNIQUE



b. SINGLE CRYSTAL TECHNIQUE

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FIGURE 33 FERROELECTRIC BISMUTH TITANATE DISPLAY

cross talk and the spacing between the stacked rows must be 0.1 c to permit the insertion of an insulation layer. Resolutions of 100 elements per inch should be attainable.

- Brightness - High brightness can be achieved since the brightness is determined only by the intensity of the light source situated behind the panel and the transmission of the incident illumination through the bismuth titanate. The transmission efficiency can be increased by polishing and coating the crystal surfaces and by using collimated and monochromatic light.

- Uniformity - Uniformity should be a problem because of the strict fabricational and dimensional tolerances required to obtain good electrical and optical uniformity.

- Contrast - Contrast ratios can be high due to the large difference between the optical extinction directions for the two electrically-switched c-axis states. A contrast ratio of 300 to 1 has been measured with collimated, normal light and 20 to 1 for light at an angle of 30°.[3] Uncollimated light will reduce the contrast, as will depolarization of the light due to any surface roughness or reflections. High contrast, therefore, requires proper polishing and surface-coating techniques.

- Gray Scale - It is anticipated that gray scale can be achieved by partial switching of the ferroelectric domains. A series of vertical dark and light bands are produced between the electrodes when c-axis electrical partial switching occurs, with the ratio of dark to light proportional to the amount of switching. These bands are integrated by the eye to form one resolution element of appropriate grayness.

- Storage - The display has inherent storage for an indefinite period. The polarization vector will remain in the switched position after the switching voltage has been removed.

- Switching Voltage - The voltages required for complete switching are a function of the c dimension of each resolution element and the length of time it is applied. For a 100-element-per-inch display operating at video rates, the switching voltage should be about 150 volts, which is too large to be provided by integrated driving circuits at this time.

- <u>Threshold</u> - Although there is no absolute switching threshold, bismuth titanate can tolerate a large number of matrix half-select pulses before the remanent polarization state is appreciably disturbed. This is primarily due to its highly nonlinear switching speed-electric field characteristics. Reference 2 indicates that for a 1000-line display in which elements must be able to withstand 1000 disturb pulses of 30 μsec each, the remanent polarization would be disturbed by only 10 percent.

- <u>Scanning Rate</u> - The addressing time per element can be as low as 1 μsec, although 10 μsec is a more reasonable value to assure complete switching. If an element is left in one state for an extended length of time, subsequent switching is slower. Fast switching can be restored by the application of several cycles of complete switching (possibly at the end of each frame) or by the application of a low level ac field during the element waiting period. To compensate for the waiting time and self-reversal effects, the width of the switching pulse should be extended to about three times that of the direct switching time requirement. This would indicate a required addressing time of 30 μsec per element, which in turn indicates the requirement for a line-at-a-time addressing in order to scan 1000 lines in 30 millisec.

- <u>Power</u> - Power requirements are low. The power dissipated within the panel due to switching of the elements along the c-axis is estimated to be about 8 milliwatts/cm^2 for a 30 frames/sec rate. Once an element has been switched, no holding voltage is required to maintain it in that state.

- <u>Lifetime</u> - The bismuth titanate display exhibits no shelf fatigue and no fatigue due to continuous electrical switching. Any depoling that occurs after a large number of c-axis reversals is generally near the ab surfaces so that the major portion of the viewing area is unaffected. The major reliability problems will occur with the complex addressing circuitry required rather than with the display panel itself.

4.1.2.1 Summary

The ferroelectric bismuth titanate display has the advantages of being a flat panel device with good resolution, high brightness, adequate contrast ratio, low power, inherent storage and minimum fatigue problems. The disadvantages are strict compositional and geometrical tolerance requirements for the crystal, fabrication and assembly difficulties with the stacked bar per line approach, high drive voltages, line-at-a-time addressing requirements for video rates with its associated complex circuitry, and the dependence of image quality on the monochromaticity and collimation of the illumination.

The ferroelectric ceramic display received a relatively high rating in the evaluation scores. Although the device is still in the very early stages of development, it appears to have great potential for the future based on the feasibility study conducted by RCA.(2) While the panel fabrication difficulties and the complex matrix addressing circuitry are both formidable problems in the development of a 1000x1000 element display, the technique is very promising due to the low size, weight and power requirements and the excellent optical performance anticipated.

4.1.3 Magneto-Optic Display

The magneto-optic display panel consists of three basic components, as shown in figure 4-4, electrical input, magnetic memory, and optical output.[4] The flat panel device is constructed on a glass substrate on which an X-Y matrix of conductors, isolated from each other, have been deposited. The next layer is an electrodeposited nickel iron film having a regular magnetic domain structure. In intimate contact with the NiFe film is a colloidal suspension of ferromagnetic particles in an aqueous solution called a Bitter's solution. After sealing with a glass cover plate, the result is a thin sandwich structure in which local optical gratings corresponding to resolution elements can be formed and used to control incident light in display applications.

The method used by General Electric to form a single resolution element is illustrated in the lower portion of figure 34 [4] By applying a burst of about 10 cycles of ac current to one conductor and a dc pulse of about 1.5 times the duration of the ac pulse to a perpendicular conductor, the coincident addressing of the particular element produces a magnetic field which in turn causes stripe domains to be oriented in the NiFe film. The domains are oriented in the direction of the magnetic field, i.e., perpendicular to the dc current. The purpose of the ac waveform is to establish a threshold by disturbing or "jittering" the domains so they may be aligned by the dc-produced field. The spatially regular domain structure at the surface of the film magnetically attracts the ferromagnetic iron particles in the Bitter's solution to form a glomerate particle grating or array. When the panel is illuminated, light diffracted by this small array of stripe domains is integrated by the eye and constitutes one ON resolution element. Erasing is accomplished by interchanging the ac and dc waveforms. The old glomerate particle grating is thermally dispersed and the new one is magnetically precipitated in the orthogonal direction. A line-at-a-time erasing can be achieved by an appropriately large ac current along that conductor.

The three orthogonally oriented diffraction gratings shown in the figure represent three resolution elements. The illumination angle is adjusted so that the first order diffracted energy from the element in the written state is directed to the viewer. The diffracted energy from the two erased or OFF

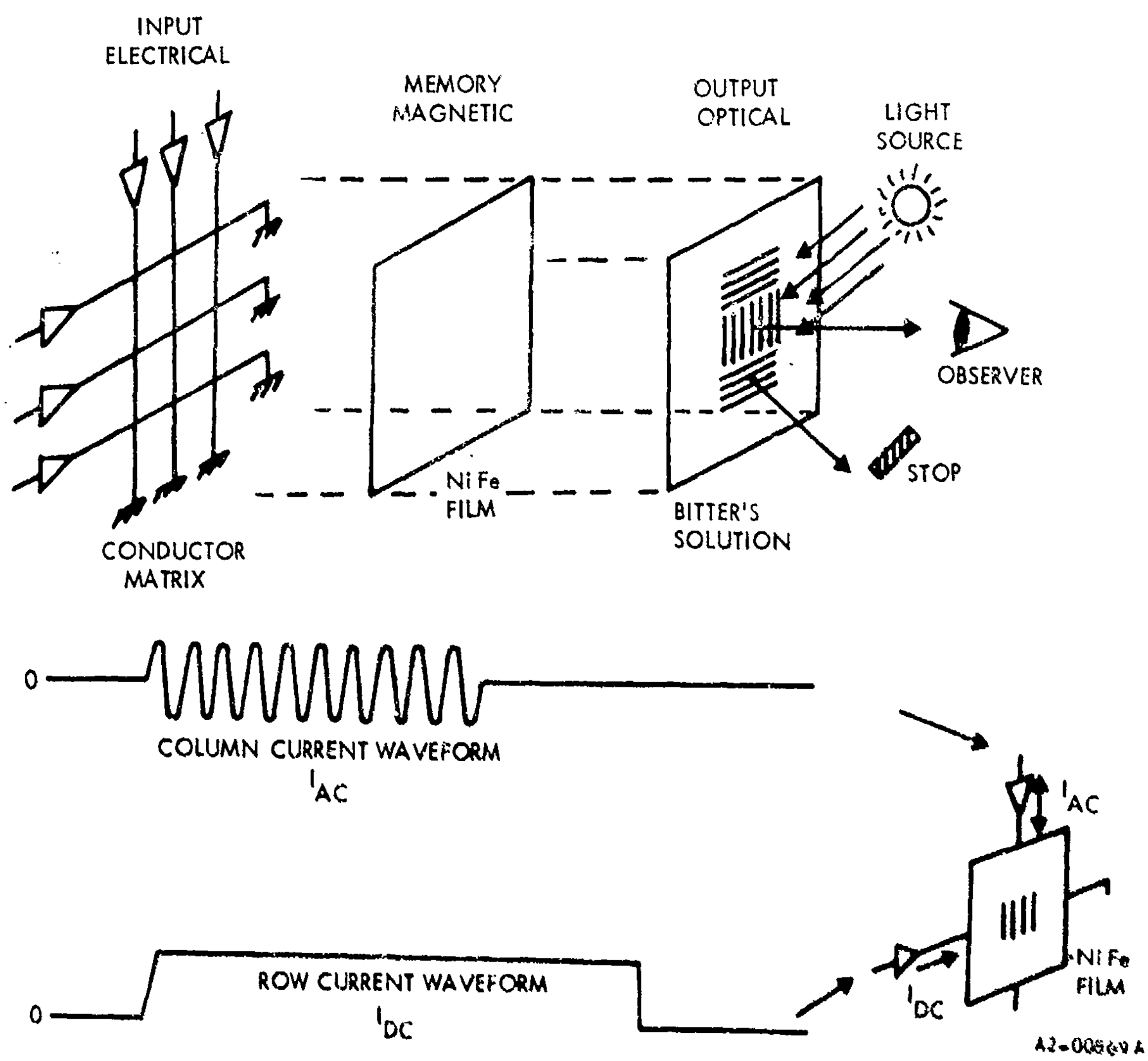

FIGURE 34 MAGNETO-OPTIC DISPLAY TECHNIQUE

elements travels in an alternate direction, is eliminated by the use of baffles, and never reaches the observer. Although the elements are bistable, that is, either ON or OFF due to the orthogonal nature of the matrix conductors and the stripe domains, some gray scale capability could be achieved but at increased addressing complexity.

- <u>Panel Fabrication</u> - The construction of the display panel has some problem areas, the most difficult being the fabrication of a magnetically efficient film (function of composition, thickness, mechanical and magnetostrictive stress effects) and the method of sealing this film with an overlay of a reactive aqueous solution between two glass plates. If batch fabrication should become practical, the panel will be fairly inexpensive to manufacture. There is no fundamental limitation on the display size.

- <u>Resolution</u> - High resolution is possible since the number of elements per inch are limited by the conductor deposition and spacing rather than by the domain structures. The size of the resolution element is also a function of the conductor size with the element area being equal to the coincident area of the X and Y conductors at the cross points. Typical element sizes range from 0.100 inch to 0.001 inch.

- <u>Brightness</u> - Display brightness is directly dependent on the intensity of the light source. Although the conversion efficiency of illuminating light into display-image light is only 1 to 5 percent for this panel, very high brightness values can be achieved (GE has demonstrated 10,000 foot-lamberts).

- <u>Contrast</u> - Good contrast ratios, which are a function of the magnetic film thickness, have been demonstrated (~30 to 1). Both brightness and contrast, however, are strongly dependent on the viewing angle due to the diffraction grating effect which is used to form the resolution elements. The wavelength dependence of the diffraction angle produces a rainbow effect as the observer changes his position. Multiple line sources of light can be used to produce a superposition of diffraction images with different wavelengths at the point of observation in order to obtain white images on a dark background. A method for illuminating the display panel uniformly must also be devised.

In the case of the liquid crystal display, the contrast is enhanced as the ambient illumination is increased. In the magneto-optic display however, the necessary positioning of light source and observer with respect to the display panel indicates that the contrast of the display will be degraded rather than enhanced under conditions of high ambient illumination.

- Storage - The magneto-optic display technique has electronically controlled persistence. The optical grating formed by locally magnetizing the film in that direction can be maintained until a reversal of the current waveform and polarity is initiated.

- Switching Voltage - Very low switching voltages are required, on the order of one volt.

- Power - Power requirements are high. A current of about 5 amps per conductor is needed to produce a magnetic field sufficiently intense to orient the stripe domains in the Ni Fe film.

- Threshold - An excellent threshold is obtained using the ac waveform to coincident current address the display elements.

- Scanning Rate - The present switching time of 10 μsec (dc - ac pulses) per resolution element is limited by the driver electronics, not by the response time of the magnetic domains. The operation of a 1,000 line display at a 1/30 sec frame time allows about 33 μsec writing time per line. At 10 μsec scan time per element, the magneto-optic display must be addressed one-third of a line at a time to achieve a 33 μsec line time. A 1000x1000 element display would then require over 300 drivers to simultaneously modulate the current in over 300 conductors, each requiring a triggering current of 1 to 5 amperes. Future optimization of the driver electronics design and reduction of the driver current requirements should increase the writing speed.

- Size - Although the magneto-optic technique is essentially a flat panel display, the required placement of the light source in front of the panel at a specific angle relative to the display surface and the viewer results in a bulky optical system. Methods of placing the illuminating optics behind the display surface are being investigated to prevent the obstruction of the observer's view.

- **Lifetime** - While the lifetime of the display surface is about 1.5 years, the life of the display panel may be affected by the life of the seal and interaction between the seal and the Bitter's solution. The aqueous nature of the Bitter's solution also makes it necessary to keep the temperature of the panel above freezing level. In addition to chemical aging, the reliability of the display system will depend on the addressing and driving circuitry. Currently, over 300 drivers would be required to address a 1000x1000 element display at video rates. This complex circuitry with 1 to 5 amps triggering current required per conductor is presently the major reliability limitation.

4.1.3.1 Summary

Although the magneto-optic display technique has the advantages of high brightness, good resolution and contrast, inherent memory and low switching voltages, it has several significant disadvantages such as a high triggering current, narrow viewing angle, bulky optical system, questionable gray shade capability, and requires 1/3 line-at-a-time addressing for video rates. At the present time, the driver electronics limit the writing speed and represent the largest contributor to the size, weight, power and cost of the display system. The device is still very early in the developmental stage, however. It is anticipated that improvements in the electronics design, the use of integrated circuitry, and reductions in current and power requirements will increase both the scanning rates and the display reliability.

4.2 ELECTRON BEAM-ADDRESSED LIGHT VALVE DISPLAY TECHNIQUES

The three light valve schemes discussed here - the cathodochromic storage-display tube, the deformographic storage-display tube and the oil film television display tube - differ from the previous three techniques in that an electron beam is used to address the active display area rather than the coincident current address of a conductor matrix. A CRT-type electron gun and vacuum tube is required in contrast to the flat panel configuration of the matrix addressed displays. A brief description of the display tube characteristics and of their ability to satisfy the VDS requirements is given below.

4.2.1 Cathodochromic Storage-Display Tube

The cathodochromic display tube uses an electron beam to produce a reversible coloration in sodalite target material and thereby store information until it is thermally erased. The storage tube currently under development at RCA Laboratories(5) uses electron guns and deflection means similar to their black and white television tubes. The target structure as illustrated in figure 35 consists of a transparent sodalite: Br powder layer in which the electron beam induced coloration occurs, a transparent heater for image erasure and a supportive transparent mica substrate mounted just inside the tube faceplate.

The electron beam scans the target and writes an image on the cathodochromic layer. When viewed in the transmissive mode, a light source is placed behind the tube. The variation of light transmitted through the layer provides a display image to the observer viewing the faceplate. The image will remain indefinitely (months to years) until it is thermally erased by the transparent heater which also serves as a charge collector during the write interval. In the reflective mode, the cathodochromic layer is aluminized and the target is illuminated from the faceplate or viewer side. The heater layer is deposited on the viewer side of the mica substrate in this case to minimize the electric field produced across the sodalite layer during erasure. The thermal erase tube is considered superior to the optical erase due to the higher contrast obtainable. In addition, the optically insensitive material used in the

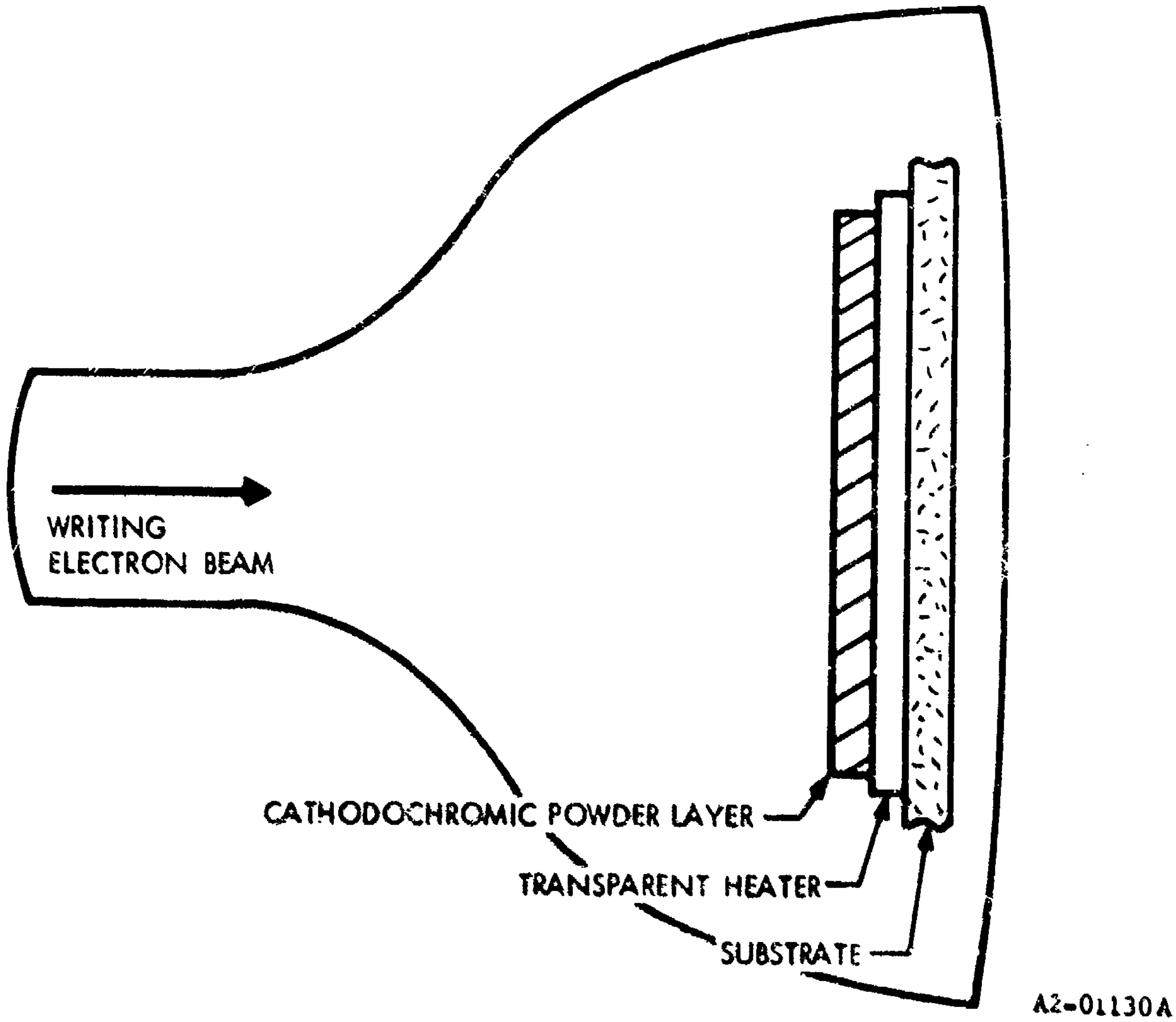

FIGURE 35 CATHODOCHROMIC STORAGE - DISPLAY TUBE

thermal erase mode allows an image to be illuminated and displayed without destroying the storage.

- <u>Fabrication</u> - The cathodochromic storage display tube is an inherently simple device, similar to the conventional monochrome TV tube, and should be inexpensive to manufacture.

- <u>Resolution</u> - The resolution is limited only by the size of the scanning electron beam spot.

- <u>Brightness</u> - Very high brightness values can be achieved since the display brightness is source dependent.

- <u>Contrast</u> - Higher contrast is attainable in the transmission mode than in the reflective mode. In the transmissive mode, all the light reaching the viewer must pass through the cathodochromic layer so that all the absorbing centers produced within the layer by the scanning electron beam affect the display image intensity pattern. In the reflective mode, it is primarily the absorbing centers in the particle layer nearest the viewer that determines the contrast ratio, therefore longer frame times are required in the reflective viewing to obtain the same contrast as transmissive viewing.

  In a 500-line display, contrast ratios of 10 to 1 have been obtained with a frame time of 60 seconds (240 μsec/element dwell time) in the transmissive mode and a frame time of 108 seconds (432 μsec/element dwell time) in the reflective mode. The contrast also determines the erase time, a longer time being needed to erase a higher contrast image.

- <u>Scanning Rate</u> - In a 1000-line display with 1000 elements per line, a frame time of 240 seconds (240 μsec/element dwell time) would be required to write a display image having a contrast ratio of 10 to 1 in the transmissive mode. The minimum time in which a 10 to 1 image can be erased is 2 seconds. Note that the VDS application requires a write time of .033 μsec/element corresponding to a 1/30 second frame time and a decay (or erase) time of less than 1/30 second in order to display dynamic images at video rates.

- Power - The major power requirement is the transparent heater layer used to erase the image in the cathodochromic layer. An erase power of 12 watts/in^2 is required to remove an image having a contrast ratio of 10 to 1 in 2 seconds.
- Size - In addition to the 5-inch tubes using 100 - 500 μa peak currents and magnetic deflection, RCA has also constructed an electrostatically deflected 8x10-inch tube with a post deflection expansion mesh resulting in 20 μa screen current.
- Lifetime - The target structure of the tube currently has a short life due to the thermal shock to the heater layer produced by repetitive erasures.

4.2.1.1 Summary

The cathodochromic display tube is a relatively simple, inexpensive CRT-type device suitable for applications in which long storage times are desirable and slow address rates do not present a problem. The fast address rates required for the VDS application (.033 μsec dwell time per element) to update a 1000x1000 element display 30 times a second rule out the consideration of this display technique at the present time.

4.2.2 Deformographic Storage Display Tube

The deformographic (DFG) display tube uses a rigid, deformable and reusable film to store a video image and allow it to be displayed continuously for an almost indefinite period of time. The basic components of the DFG display system are shown in figure 36 . The tube contains a write gun which produces a modulated electron beam that scans the DFG film and deposits an electrostatic charge pattern proportional to the input signal. Developmental tubes have allowed the electron beam to impinge directly on the DFG film or to write the charge information on a mica substrate with the DFG film deposited on the opposite side. The film can then be maintained in a separate vacuum chamber. The electrostatic force between the latent charge pattern on one side of the film and a grounded plane on the other causes the DFG material to distort in the form of a depth-modulated diffraction grating. By placing this grating in the image plane of a schlieren optical system, the amplitude of the

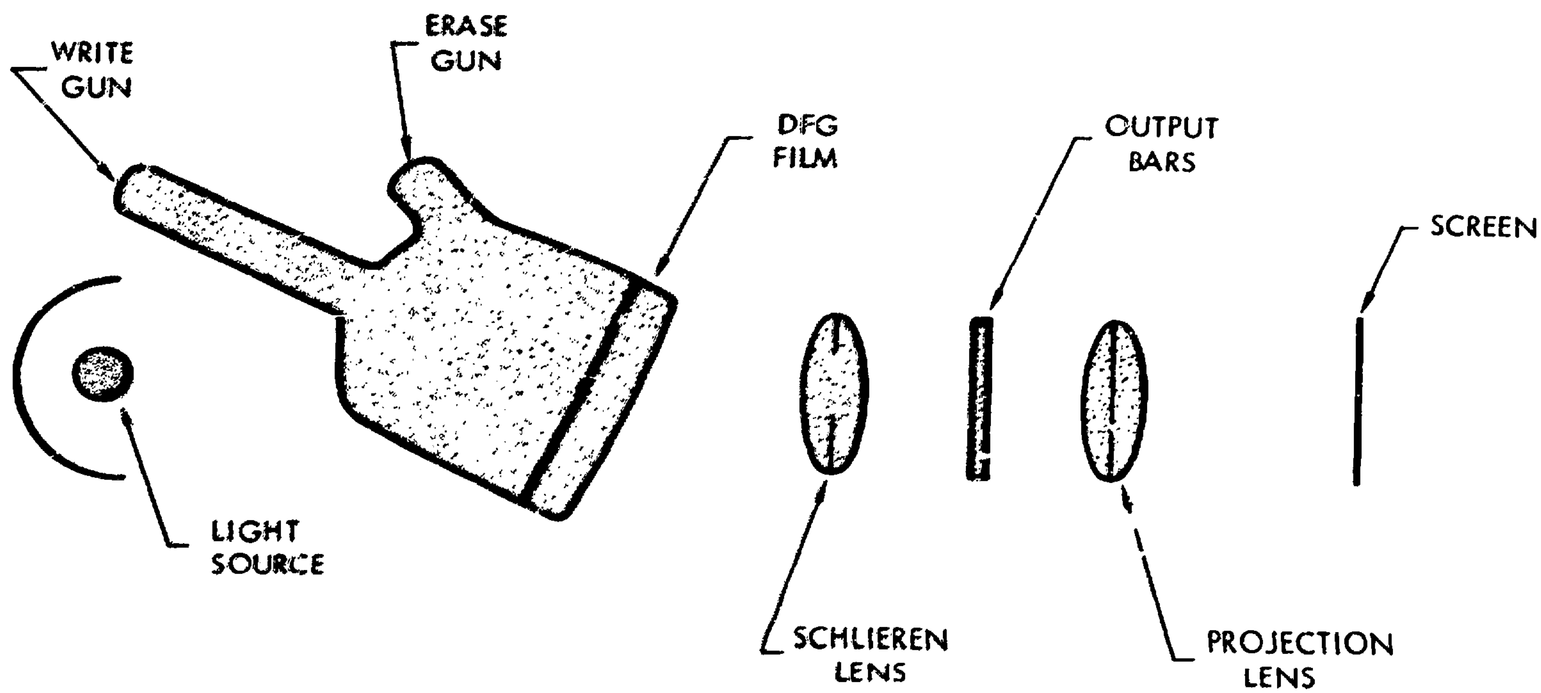

FIGURE 36 DEFORMOGRAPHIC STORAGE - DISPLAY TUBE

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deformation at each point on the film determines the angle at which the incident light passing through the schlieren input bars is refracted and correspondingly how much light will travel through the schieren output bars to the display screen. If the input slots of light are initially imaged onto the output bars so that no light reaches the screen when the film is smooth, the subsequent deformation of the film by the image charge pattern will result in a brightness pattern on the screen proportional to the depth of the groove created in the film surface.

The film deformation can be removed by heating the film to a temperature where the restoring surface tension exceeds any residual electrostatic force or the surface can be made smooth by flooding the film with electrons from the erase gun, as shown in figure 36 , to achieve a uniform charge distribution over the target area. The present inability of the DFG film to deform rapidly enough to allow imaging information to be written with good contrast at video rates, and the length of time required to erase that deformation pattern completely in preparation for the next frame presently prohibit television-type operation.

- <u>Fabrication</u> - The DFG display tube is currently in the developmental stage. The write gun, erase gun and deflection means are similar to conventional CRT storage tubes. Therefore, the primary fabrication problem is the DFG film, its composition, resistivity, thickness, resilience, uniformity, flow and degradation characteristics, etc.

- <u>Brightness</u> - The display brightness is source dependent. Note, however, that the use of schlieren optics and a projection system result in a relatively large light loss and therefore require a high power light source to achieve high screen brightness levels.

- <u>Resolution</u> - The resolution is limited only by the electron beam spot size and can thus be very high.

- <u>Contrast</u> - The contrast achieved is a function of beam current and writing speed. IBM is currently obtaining a contrast ratio of 30 to 1 for a 250 nanosec dwell time per resolution element (10 shades of gray).[6] An estimated 10 to 1 ratio can be achieved in a 1000-line display with a dwell time of 30 to 50 nanosec per element (5 shades of gray).

- o **Scanning Rate** - If the present scanning rate of 250 nanosec per resolution element can be reduced to 30 nanosec, a 1000x1000 element display can be written in 30 millisec, which is equivalent to the TV frame time. The continual display of video information, however, will depend on the erase time. The IBM tube, which currently requires a 60 millisec erase and decay time (equivalent to 2 TV frame times), anticipates a reduction to 0.5 millisec.[6] Should the development of the IBM tube proceed as expected, a 1000-line storage display tube will be capable of video rate display with 5 shades of gray when operating in a nonstorage mode.
- o **Power** - The storage tube itself requires very little power (~8 watts). The major power requirement is the light source (~150 watts).
- o **Size** - The DFG display system consisting of tube, optical projection system and driving electronics will require a volume of about 2 cubic feet.
- o **Lifetime** - The lifetime of the DFG storage-display tube will be limited by the degradation and aging of the deformable film. IBM anticipated a 400 hour MTBF for the tube and the light source in a 1000-line development model. Current operation at room temperature is expected to be extended to a -55 to 50°C range. Ruggedization of the system for a cockpit environment will be difficult due to the schlieren optical system which is highly sensitive to vibration.

4.2.1.1 Summary

The deformographic display tube has the advantages of high brightness, excellent resolution, inherent storage, and good contrast and gray scale when operated in the storage mode. Its disadvantages include nonuniformity problems, large size of complete unit (as compared to a flat panel display), short lifetime, and vulnerability of the schlieren optics to vibrational misalignment in a cockpit application. The main performance characteristic which must be improved for application to the vertical display system is the write-erase cycle time. The write time per element required to achieve a contrast ratio of 23 to 1 must be reduced to ~0.03 μsec in order to write a complete frame (1000x1000 elements) in less than 1/30 second. The erase and decay time must also be reduced so that the image can be completely removed within that same frame time.

The present inability of the DFG tube to operate at video rates with adequate contrast in the nonstorage mode and the difficulties associated with the placement and maintenance of a large size, low life, projection-type display unit in a cockpit caused the DFG technique to receive a relatively low rating for this particular application.

4.2.3 Oil Film Display

The oil film light valve technique used in the Eidophor and the G.E. TV projector system is one of the few display devices which is in production and can be purchased off the shelf. It is a large size projection display system capable of black and white or color television presentation. The basic components, as shown in figure 37, consist of a light source, a set of schlieren input slots, an electron gun, an oil surface on a rotatable disk, schlieren lens, output bars, projection lens and display screen.[7]

The scanning electron beam is modulated by the video input signal and writes a corresponding charge pattern on the fluid surface. Electrostatic forces produced by the latent charge distribution result in the formation of grooves in the oil film, thus creating a depth-modulated diffraction grating. The schlieren optical system is initially adjusted so that no light passes through to the screen when the oil film is smooth. A subsequent deposition of charge at a point produces a groove which refracts the incident illumination through the output bars and forms a spot of light at a corresponding point on the screen. The brightness of the spot is proportional to the depth of the oil groove. The restoring forces in the liquid, consisting of hydrostatic pressure in the fluid and surface tension forces return the liquid to its original smoothness rapidly enough to allow the display of dynamic images at video rates. The display is not designed for storage capability at this time.

- <u>Fabrication</u> - The major fabrication problem is the sealed light valve tube, including the electron gun and the deformable fluid. The fluid viscosity, thickness, surface tension and electrical conductivity must be optimized to adjust the decay time of the groove to about one field period (1/60 sec). G.E.'s sealed tube contains its own fluid supply and vacuum pump. The rotating disk is driven through the glass wall and

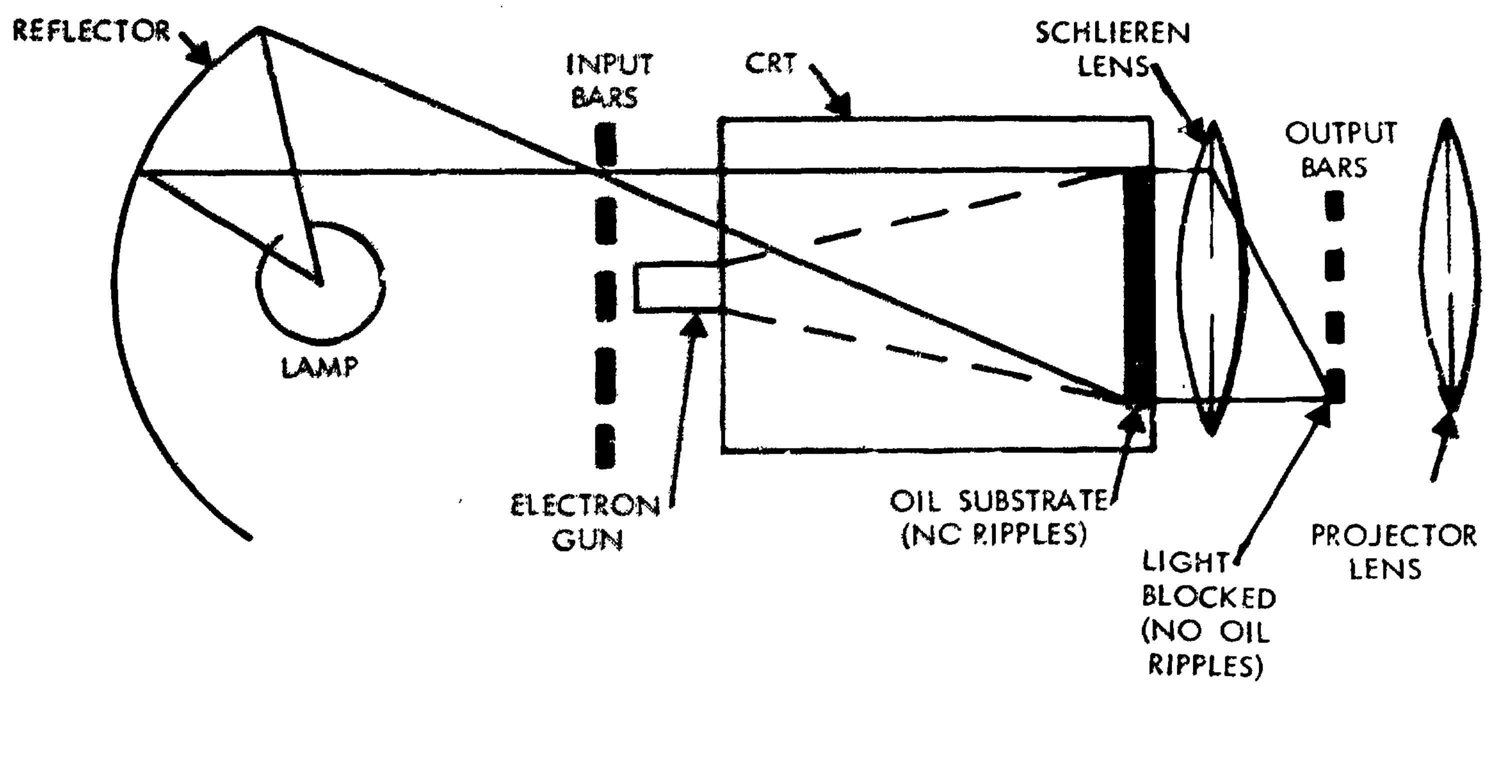

FIGURE 37 OIL FILM LIGHT VALVE DISPLAY SYSTEM

brings up a fresh layer of fluid from the sump at a speed of three revolutions per hour.[8] Because the fluid film is in the same chamber as the electron gun, a vacuum pump is required to continually remove hydrogen and broken down organic vapors. Although the construction appears complex, its practicality is proven by the fact that the system is in production and being used in commercial applications.

- Resolution - Resolution is limited by the size of the electron beam spot so that 100 lines per inch is easily achieved.

- Brightness - The display brightness is source dependent, although the loss in optical efficiency due to the projection system will increase the power requirements of the light source.

- Contrast - Contrast ratios are excellent - 100 to 1 for black and white and 50 to 1 for color. Ten shades of gray are easily achieved.

- Color - In the color television display, the schlieren output slots are made sufficiently narrow to admit only one of the primary colors of the diffracted light spectrum. Since the grating spacing on the fluid surface determines the diffraction angle, it also determines the color of the picture element on the screen. By writing three differently pitched diffraction gratings - one for each of the primary colors - within each picture element, color selection can be achieved.

- Scanning Rate - The oil film light valve technique is currently capable of television projection presentation. The ability to provide a dynamic display at video rates is due to proper choice of the build-up and decay times of the electron beam-impressed grooves in the fluid surface. The fluid must be able to deform rapidly enough so that an image can be written with adequate contrast in less than a field period. The decay time during which the restoring forces return the fluid surface to its initial smooth state must also be adjusted to about one field period. If the grooves decay too quickly, the light valve will be ON for only a portion of the available time, resulting in lower efficiency and decreased brightness. Too long a decay time would produce higher efficiency but also a "trailing" image. Going from a 500-line to a 1000-line system,

yet maintaining a 1/30 second frame time, will require that four times the initial number of resolution elements be scanned in the same time period. The fluid characteristics which determine the groove build-up and decay times will have to be optimized for this design.

- Power - Power requirements for the present system are high (~1650 watts). However, G.E. feels a reduction to ~400 watts can be achieved with proper design of the 1000-line system.

- Size and Weight - The television projection system currently on the market, which was designed for large screen display applications such as classrooms and movie theatres, is both large (~20 cubic feet) and heavy (~460 pounds). With proper design, a small screen cockpit projection display could be constructed; however, the minimum size estimate is 8 ft^3 and minimum weight is about 160 pounds.

- Lifetime - In previous oil film light valve systems, the oil had a relatively short lifetime due to electron beam irradiation. With the development by G.E. of a synthetic fluid, a special cathode and electronic vacuum pump, a lifetime in excess of 1000 hours has been achieved.

4.2.3.1 Summary

Although the design of the oil film light valve display system appears complex, it is obviously practical since the system is currently used in closed circuit projection television for education, commercial and military applications. The most significant advantage of the oil film technique is its present capability of displaying video images at TV rates with good resolution, high brightness and contrast ratio, good gray scale and demonstrated color presentation. Its major disadvantages are large size, weight and power requirements, relatively high cost and anticipated difficulties in producing a MIL spec qualified system for cockpit application. The oil film display received only a moderate rating in the display techniques evaluation primarily because of the stringent size, weight, and power limitations established for the Vertical Display System.

4.3 AC AND DC PLASMA DISPLAYS

The plasma display consists of a rectangular matrix array of cells within which a gas discharge occurs. A considerable amount of development effort is occurring in two different classes of plasma displays - ac and dc. Both types are generally constructed in a sandwich form consisting of two outer dielectric layers enclosing a center cavity (usually honeycombed except in low to moderate resolution ac plasmas) with etched holes (see figure 38). The panel is evacuated, baked, and then filled with a gas mixture containing mostly neon.

The addressing electrodes consist of an orthogonal set of transparent conductive substrates which are vapor deposited on the inside (dc) or outside (ac) surface of the glass plates. The ac plasma applies voltages to the appropriate row and column of the externally deposited electrodes with capacitive coupling of the addressing current into the cell. The capacitive reactance isolates the cells from the row and column electrodes and any combination of cells can be on at one time. The dc plasma uses internally deposited electrodes and can be designed to require less driving circuitry than the ac plasma. The major difference between the ac and dc Plasmas is that the ac plasmas are inherently capable of exhibiting internal memory whereas the dc Plasmas are not normally available with internal memory.

The bistable characteristic of the ac plasma display cells in which the cells can reside in special normal modes or states of equilibrium provides memory capability in addition to the light emitted during the discharge process. The bistable characteristic is due to the accumulation of charge created by the discharge. If the charge is removed, the full firing voltage must be reapplied to reignite the discharge. Typically the entire array of cells is initially excited by the coincidental arrival of an ac firing and sustaining voltage signal at the selected cell. The subsequent arrival of the sustaining voltage (which by itself is of insufficient magnitude to ignite gas discharges in any of the elements) can cause ignition in those cells where an appropriate residual charge is present on the walls due to a previous discharge. The voltage across the cell will be augmented and a new discharge will be ignited. Electrons and ions again flow to the dielectric walls extinguishing the discharge; however, on the following half cycle the charge again augments the external

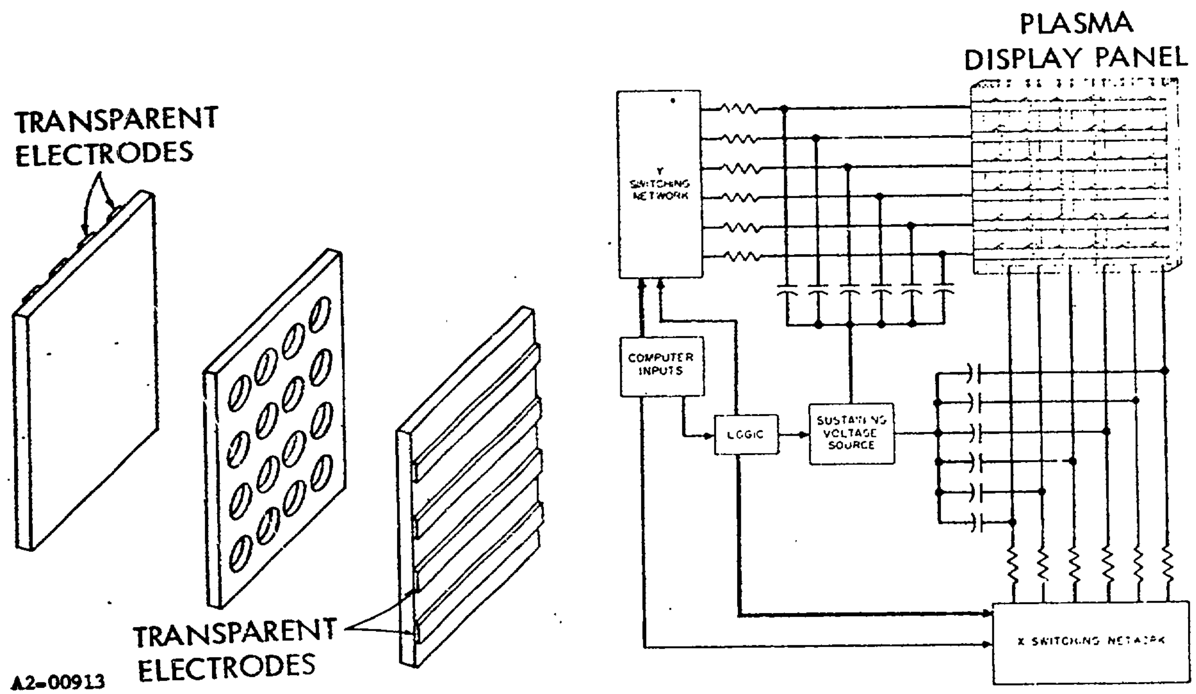

FIGURE 38 PLASMA DISPLAY

sustaining voltage and makes possible another discharge in the opposite direction. A sequence of electrical discharges can be sustained once started by an alternating voltage signal that by itself could not initiate the sequence. Selective write and erase is a valuable feature of the ac plasma.

Plasma displays usually use either a UV source of light to back light the panel to supply a source of initial electrons (by photoelectric emission) for cells that are off so that the cells can be fired reliably at any specified time or alternatively keep a series of border cells around the periphery of the display permanently lit for the same purpose. If neither of these techniques is used, some other mechanism must be employed to ensure reliable operation. Some dc plasmas have a self-scanning feature which utilizes a back panel in which a glow is maintained behind the line being addressed to provide a reliable starting mechanism as well as providing a method of reducing the number of driving circuits required.

The major characteristics of the ac and dc plasma panel displays are itemized and discussed below.

- Panel Fabrication - The sandwich construction of the plasma panel provides a relatively rugged, flat design which is amenable to batch fabrication at relatively low cost. AC plasma panels with a dot spacing up to 60 per inch do not even require an internal honeycomb structure to separate the cells. However, for resolutions of 80 to 100 dots per inch, cell separation is required to prevent cross talk (excitation of adjacent elements due to spreading or fringing of the applied fields) in ac plasmas. However, the addition of the center panel generally increases the magnitude of the addressing voltages. To date, dc plasmas have been limited to approximately 50 dots per inch, although higher resolutions should be possible if new materials are developed.

- Contrast and Gray Scale - Relatively high contrast ratios (approximately 30 to 1) can be obtained with plasma panels. However, the biggest difficulty is obtaining gray scale without losing other desirable characteristics. Two types of techniques are currently being investigated to incorporate gray scale into the ac plasma panel. The first class of techniques implements gray scale at the cost of eliminating the inherent

memory mechanism. Continuous brightness variation (gray scale) should be possible in this mode. However, the loss of memory reduces panel brightness considerably. For this reason this class of techniques will probably not be usable for the VDS application. The second class of techniques does not sacrifice memory when gray scale is added, however continuous variation is not possible. In fact, due to the available memory margin available, only a few discrete levels of brightness will be available. Thus far only four levels (including OFF) have been demonstrated over a relatively small area. As the display areas get larger, the operating memory margin of ac plasma is generally reduced. This technique may reduce overall panel reliability and require frequent maintenance. However, considerable effort is being devoted to solving these problems and potential for extending the number of gray shades to perhaps six or eight levels exists in the future. Both panel and electronics complexity can be expected to increase considerably with the addition of gray scale.

DC plasmas should be able to incorporate gray scale without considerable difficulty, however no new results in this area have been reported. Six to eight shades of gray certainly seem feasible if uniformity problems can be eliminated.

- Switching Voltages - The firing voltage presently used in ac plasma panels is of the order of 70 - 100 volts and the sustaining voltage is approximately 150 - 160 volts. These voltages presently preclude the use of LSI technology, however hybrid circuit techniques may be used.

- Power - The present avarage power level for a 512x512 resolution element video display with all elements in an ON state is approximately 500 watts with peak power in excess of 1 kw. The major portion of the power being dissipated within the panel itself does present some heat transfer problems, which requires careful thermal design.

- Scanning Rate - The addressing time per display cell is approximately 25 μsec, which necessitates the use of a line-at-a-time addressing circuitry for a 1000x1000 element video display. This circuitry would probably require the use of 1000 modulation drivers, 1000 sample-and-hold circuits, and 1000 vertical driving switches. This amount of relatively complex driving circuitry has a rather severe impact on the total system reliability.

o **Brightness** - AC plasma panels with memory have achieved brightness levels in excess of 650 FL in application with relatively low duty cycles and element densities (such as 300-element alphanumeric displays). The use of phosphors to convert the UV energy emitted in the discharge process into usable light output in the usable spectrum offers potential for increasing the light output somewhat. Currently, 512x512 element ac plasma displays at 60 LPI resolution operate at an average spot brightness of 35 foot-Lamberts. Increasing light output much above present limits may create some thermal problems in the panels as efficiencies are not very high. The dc plasma provides much lower light output because of the lack of memory. The dc plasma would certainly require the use of a memory element to be considered for the VDS application. The technique for implementing memory into the dc panel has not yet been successfully demonstrated on a large scale.

4.3.1 Summary

The ac plasma offers good potential for use in the VDS application. Its major advantages are the memory characteristics which may enable the display to provide adequate brightness in the future. The plasma panel is relatively simple, rugged and inexpensive to manufacture, and the research and development effort is relatively high. A 512x512 video graphic plasma display is presently in production and, although relatively low in brightness, the technology is rapidly being advanced. The main disadvantages at present are lack of brightness and gray scale, and slow response time which will necessitate the use of a line-at-a-time addressing technique for the VDS application. The dc plasma does not appear to be an attractive display technique for the VDS application because of the inherent low brightness due to lack of memory.

4.4 LASER DISPLAYS

There are two main categories of laser displays; those systems based on a scanned laser beam and those systems utilizing holographic techniques. The scanned laser beam technique represents the most advanced state of development which may be considered for a future VDS. The holography displays although at present not well developed offers future potential for a three dimensional imaging display.

A typical scanning laser display technique (illustrated in figure 39) consists of a continuous wave gas ion laser beam such as argon, helium neon, xenon, or krypton which is pumped by RF or dc excitation to cause lasing action. The output light beam from the laser is modululated to control its intensity by an electro-optical polarization device such as a pockels cell and deflected to cause a scanning action on the display screen. The deflection can be implemented by three different techniques 1) mechanical methods such as the deflection of a prism or mirror, by a motor, or piezoelectric crystal, 2) diffractively by altering the distance between the lines of a diffraction grating by ultrasonic vibrations in a medium, and 3) refractively by changing the index of refraction of a transmitting fluid or crystal by means of an electro-optical effect.

Several laser video displays have been demonstrated, one utilizing a 525-line scanning standard, with a 5 MHz bandwidth, and another with a 1029-line scanning standard and a bandwidth capability in excess of 22 MHz. The brightness is typically of the order of 20 - 30 FL for screen sizes of 5 - 20 Ft^2.

The most serious fundamental shortcoming of the laser technique for the VDS application is the low efficiency of energy conversion from electrical input to light output which is of the order of 0.01% for the high brightness gas ion lasers. In order to get as little as one watt of light output 10 kw of electrical input is required. Laser displays are also very bulky at present but could be made more compact with future development effort.

The major characteristics of scanning laser displays are listed below:

o   <u>Fabrication</u> - Laser displays have been fabricated with relatively large screen sizes for projection purposes, a smaller screen size in a ruggedized form is required for the VDS.

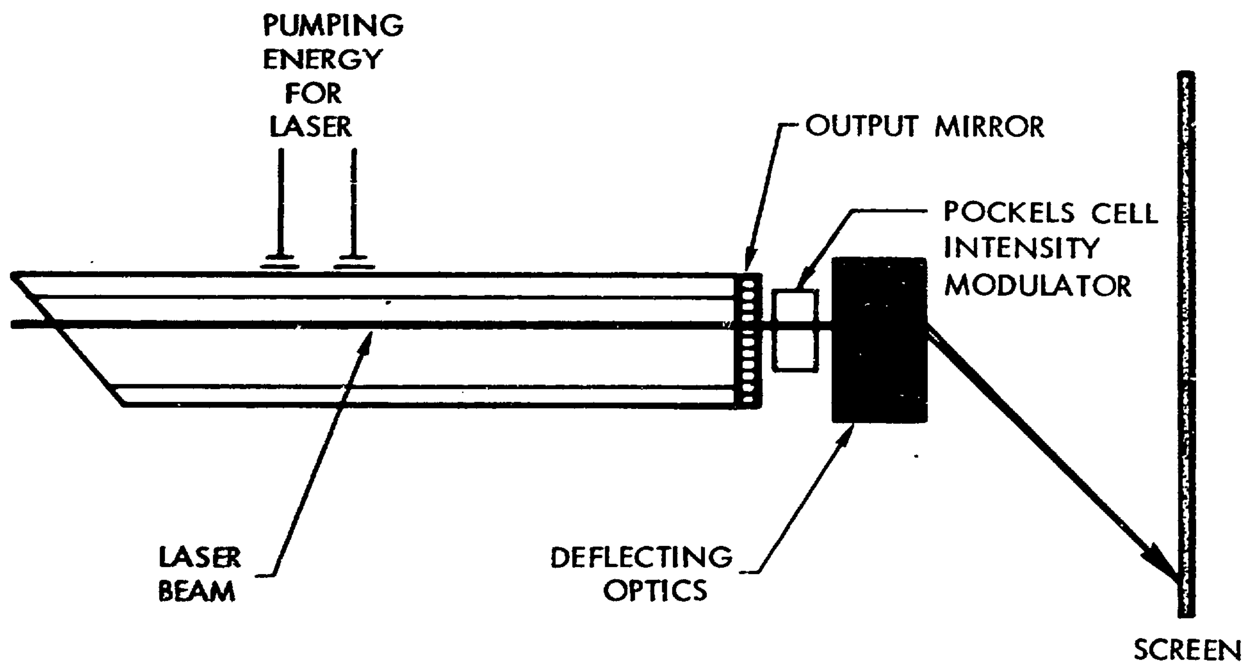

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FIGURE 39 LASER DISPLAY

o Contrast Ratio and Gray Scale - The contrast ratio that has been achieved is in excess of 100 to 1 with 10 shades of gray which is required for the VDS. Because of the monochromatic nature of the light output from the laser a narrow band spectral bandpass filter can be used to suppress the ambient sunlight. The utilization of this technique permits a reduction in the laser output by a factor of 4.

o Power - The estimated power input for a laser VDS would be approximately 10 kw, which is far in excess of an acceptable value. Some improvement in laser efficiency may be anticipated however, it is doubtful that an acceptable power input may be achieved by 1975.

o Color - Full color laser display systems have been demonstrated. One system uses an argon ion laser for green (23 milliwatts) and blue (130 milliwatts) wavelengths and a helium neon laser for red (100 milliwatts) for a total flux of 44 lumens.

o Scanning Rates - Laser scanner displays have been demonstrated with 1023 scanning standards and 22 MHz bandwidths which exceeds the performance design goals of the VDS. The laser technique is considered to be the most advanced in scanning capability.

o Lifetime - Laser displays are anticipated to have operational lifetimes of approximately 1000 hours.

4.4.1 Summary

Laser scanner displays are probably in the most advanced state of development in respect to fulfilling the operational performance goals of the VDS. However, the serious fundamental limitations of low conversion efficiency results in an excessive system power consumption and excessive cooling requirements. The system would also be very voluminous and inferior to presently operational CRT systems in these respects.

4.5 LIGHT EMITTING DIODES

The light emitting diode is a two terminal semiconductor device that produces light by means of a radiative recombination of carriers in a forward-biased p-n junction. The wavelength of the emitted light depends on the

material used. Figure 40 is a plot of the luminous efficiency curves for various light emitting diode materials. The light output (luminous power) in millilumens is plotted as a function of the input current in milliamps for a junction area equal to 0.15 mm^2 (a 15x15 mil diode).

Red light emitting GaAsP diodes with brightness in excess of 2500 FL, at an output current density of 50 A/cm^2 have been demonstrated. These diodes are commercially fabricated by means of a zinc diffusion process in vapor phase epitaxial GaAsP. Diodes of GaP doped with zinc and oxygen are grown by means of liquid phase epitaxial techniques. These devices have demonstrated quantum efficiencies in excess of 7 percent. However, due to the longer wavelength of emission, 7000 A for GaAsP, the human eye sees the lower efficiency of GaAsP diodes (quantum efficiency $\approx$0.2 percent) as being equivalent to a GaP diode with a quantum efficiency $\approx$1 percent. The state of materials development for GaAsP which is fabricated by vapor phase epitaxy on GaAs substrates is much more advanced than that for GaP fabricated by liquid phase epitaxy on GaP substrates. High performance epitaxial layers with good uniformity have been commercially produced with areas greater than 2 in^2, and small monolithic devices have also been fabricated from this material.

Light emitting diode structures can also be fabricated which couple the infrared emission from GaAs diodes into special phosphors which are capable of converting the infrared into visible light emission. The diode is coated with a layer of small phosphor particles consisting of mixed rare earth fluorides held in an adherent binder. The infrared energy emitted from the diode excites the trivalent rare earth ions in the phosphor to a more energetic visible emitting state due to the sequential absorption of two or more photons emitted from the p-n junction. The advantage of these diodes is their ability to emit blue and green light with a suitable choice of phosphor. It has been estimated that an overall efficiency of 2 percent red, 1 percent green, and 0.1 percent blue is possible for GaAs phosphor combinations. This is comparable to GaP in the red and is far better if it can be achieved in the green or blue. The diodes will have to be driven hard to achieve these levels of efficiency because the excitation of the phosphor is a two-step process which varies as the square of the emitting intensity below saturation.

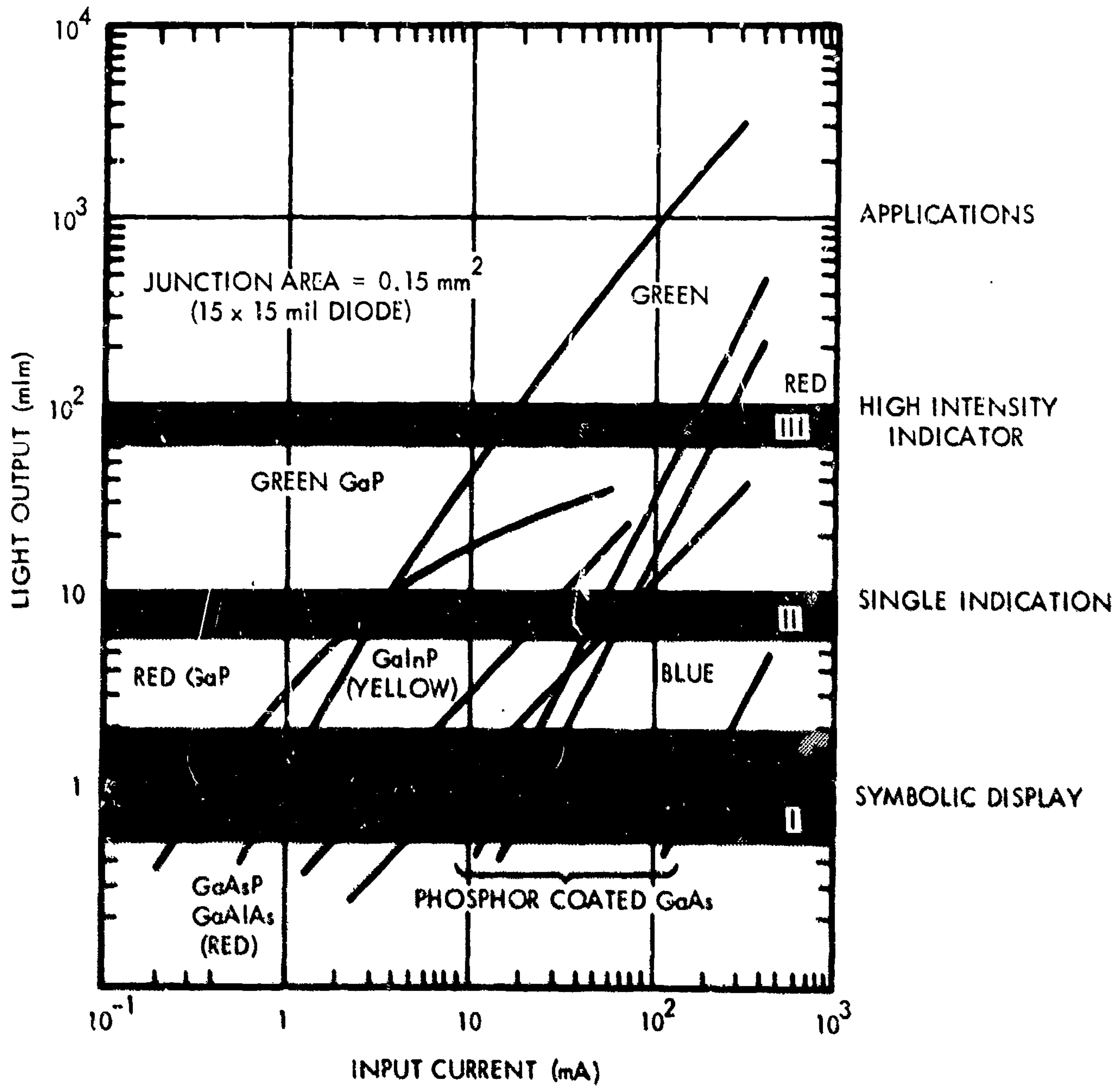

FIGURE 40 LED LIGHT OUTPUT VS INPUT CURRENT

The operating voltages and currents required by LED devices makes them ideally suited to large scale circuit integration technology. Vapor phase epitaxy or bulk single crystal growth plus planar technology can be used to fabricate relatively large size modular displays. It is also essential that the LED technology be compatible with silicon memory circuit technology because of the brightness requirement or the VDS application.

The major characteristics of the LED matrix display are itemized and discussed below.

- <u>Fabrication and Cost</u> - The largest LED arrays constructed to date are approximately 70x70 arrays on a 1-inch-square single crystal GaAsP wafer. The uniformity of these arrays was reasonably good (20% deviation in average brightness). However, uniformity from wafer to wafer varies as much as 50% in presently available LED's. The cost of LED's constructed by present techniques is predicted to fall to approximately 5¢ each by 1980. This represents a cost of approximately $50,000 for an assembled VDS display. While costs of this magnitude seem prohibitive, a further reduction of a factor of three or more may make the LED approach feasible for the VDS. A significant reduction in cost would be achieved if techniques are developed to fabricate LED's on a less expensive material. Of particular interest is the use of large poly-crystalline GaAsP wafers.

- <u>Resolution</u> - Presently LED matrix arrays are being fabricated with a resolution of 60 diodes/inch. It is expected that 100 diodes per inch can be achieved by 1975.

- <u>Brightness</u> - Low brightness is the greatest problem for an LED display for the VDS application. The present maximum brightness for GaAsP LED's is 10,000 to 50,000 foot-Lamberts operating at 100% duty cycle. For a 10^6 element display requiring 50 foot-Lamberts average brightness, each LED element could have a duty cycle no less than 1/1000. In an application with 10^6 resolution elements, 1000 LED's would have to be scanned simultaneously. The incorporation of a memory element for each LED within the display is a possible solution to the problem of brightness in very large

arrays. However this approach greatly increases the fabrication complexity and parts count of the total display system and degrades system reliability.

- Contrast and Gray Scale - Because of the monochromatic light output from LED's the contrast ratio of the display panel operating in high ambient illuminations can be greatly enhanced by the use of a narrow spectral bandpass filter system. This system can be incorporated over the LED array to suppress the ambient sunlight that is incident on the display. It is estimated that a brightness level of 600 FL on the display screen can supply a sufficiently high contrast ratio to permit 10 shades of gray scale which can be obtained by utilization of pulsewidth modulation techniques.

- Power and Thermal Considerations - The brightness of an LED is directly proportional to the current through the junction and therefore nearly proportional to the power dissipated. For 500 foot-Lambert average brightness, the power required for one 0.008-inch diameter LED element may be as high as 5 milliwatts. This would lead to a total power requirement for the VDS display of over 1000 watts with all elements on, such as in TV-mode operation. This is clearly unacceptable; however, improvement by a factor of 10 is possible. This will require large advances in material purity technology and fabrication techniques. Even with an efficiency improvement by a factor of 10, the display will still dissipate over 100 watts. Since the light output of the LED elements falls 10% with each 10-degree temperature rise, careful consideration must be given to heat-sinking of the display panel.

- Scanning Rates - The response time of an LED is approximately 10 ns, which is sufficiently fast to present no problem for the VDS application.

4.5.1 Summary

Light emitting diodes may become practical for large area video displays such as the VDS in the future. The main disadvantage is lack of brightness which requires the use of a storage element with each display element or possibly line-at-a-time addressing if improvements can be made in diode efficiency.

The physics of the problem is well understood and theoretically there is potential for factors of 20 to 50 improvement in quantum efficiency depending on the material selected. Advances in technology will undoubtedly come, but perhaps not early enough to fulfill the VDS design goals in time for a 1980 era application.

4.6 ELECTROLUMINESCENCE DISPLAYS

Electroluminescence (EL) is the phenomenon whereby light is emitted from a semiconductor material under the direct stimulation of an electric field. The generation of this light is caused by the recombination of free charge carriers which are produced in the material by the electric field. There are many types of luminescent devices. However, the so-called "intrinsic" or "powder" luminescence devices offer the greatest interest for the VDS. Intrinsic electroluminescence occurs in materials of the phosphor class, that is, small aggregates of semiconducting particles held together by a suitable binder. Under the application of a strong alternating field, light is produced. A typical EL cell consists of a transparent conductive glass substrate (usually tin oxide, indium oxide, or gold conductors) upon which the phosphor/dielectric layer is applied by any number of means such as spraying, silk screening, or settling. An electrode is applied to the opposite or rear surface of the substrate. The rear and/or the front electrode may be segmented to form any pattern of light-emitting area desired.

The most common of the EL phosphors is zinc sulfide (ZnS) modified by the addition of other materials (dopants) to produce electroluminescence. Materials such as Cu and Al are generally used as the "activators", and a halogen such as Cl or Br is generally used as the "coactivator". The choice and amounts of the material used affect the color, voltage, and frequency response, as well as the lifetime of the cell. Modifications of the basic material, such as the alloy systems zinc sulfoselenide and zinc cadmium sulfide, together with appropriate dopants also produce acceptable luminescent properties.

The response of EL cells is initially dependent upon the preparation of the material itself. Most of these materials do obey general functions which are common and construction of the cell plays an important role in the optical and electrical characteristics.

Practical limitations on the amount of voltage that can be applied to a cell are determined by the voltage breakdown of the cell. Cells are commonly designed to operate at a few hundred volts rms. The upper practical limit of frequency is generally determined by capacitance-loading effects and by the fact that cell maintenance or lifetime varies inversely as the frequency.

The characteristics of an EL cell are highly dependent upon the construction of the cell. Factors such as phosphor concentration, thickness of cell, and dielectric constant of the embedding media all affect the performance of the cells. However, none of these effects is independent.

Since the cell is constructed by suspending the EL particles in a dielectric binder, the amount of voltage impressed across the electroluminescent particles is a function of the dielectric constants of the phosphor and the embedding dielectric. The higher the dielectric constant of the binder, the more voltage is impressed across the panel.

The light flux emitted per unit volume is related to phosphor volume fraction (ratio of phosphor volume to total volume) and the higher the concentration of phosphor particles, the higher the luminance. As the phosphor volume becomes larger, the luminance cannot continue to increase, since eventually there will not be enough dielectric to completely surround the phosphor particles and the field strength impressed across them will diminish. There is consequently an optimum ratio of phosphor to dielectric that yields the highest luminance.

The major characteristics of electroluminescent displays are discussed below.

- <u>Panel Fabrication</u> - EL panels use sandwich structure construction consisting of an EL layer, a nonlinear resistive layer (NRL) and two sets of orthogonal electrodes. The NRL layer provides the isolation required so that half voltage pulses do not appear across the EL layer and cause it to luminesce at those points. This type of construction results in a compact, rugged, flat panel structure that is relatively low in cost.
- <u>Resolution</u> - The display panel resolution is limited mainly by the electrode deposition which can meet the VDS design goal of 100 dots per inch. The spot size is determined by the area of crossover of the electrodes.

- <u>Contrast, Gray Scale and Brightness</u> - Contrast ratios in excess of 30 to 1 are achievable with 10 shades of gray scale. However the inherent lack of display brightness (<50 FL) makes it very unlikely that many shades of gray could be detected in a high cockpit ambient illumination (10,000 FL).

- <u>Lifetime</u> - The use of high voltage and high frequency in addressing EL panels to achieve high brightness outputs leads to relatively short panel life (<1000 hours).

- <u>Switching Voltages</u> - EL displays require the use of 200 - 600 volts RMS to achieve relatively high display brightness, which precludes the use of LSI circuit technology.

- <u>Power Requirements</u> - It is estimated that moderately high power inputs would be required to drive an EL panel display at the high output brightness levels required for the VDS application. The major power would be dissipated in the driver circuits rather than the panel itself due to the rapid charging and discharging required of the display element capacitances.

- <u>Scanning Rates</u> - EL panels have been designed to operate at video rates with 525-line scanning standards. However, because of the relatively slow switching time (10 μsec) and inherently low brightness levels, line-at-a-time addressing is required.

4.6.1 <u>Summary</u>

EL display technology is one of the most advanced of all the display techniques considered. However, the inherent lack of brightness and relatively short lifetime of EL panels does not make the EL a very attractive candidate for the VDS application.

4.7 <u>DIGISPLAY</u>

The DIGISPLAY is an electrostatically switched, digitally addressed electron beam scanner which has been under development at Northrop for several years. The DIGISPLAY utilizes an areal electron source followed by a series of very thin, apertured control plates which are aligned and act collectively to generate scanning electron beams. The position of the beams is determined

by digital addressing signals applied to patterned electrodes on the control plates. By switching the plate voltages sequentially, an electron beam scanning pattern is achieved. The scanning beams are proximity focused onto a phosphor screen where they form the displayed image (see figure 41).

The DIGISPLAY, which can be characterized as a dot matrix display with electron beam address, combines many of the advantages of other dot matrix displays (e.g., digital address, inherently high linearity, flat panel construction) with the advantages of the CRT (e.g., good gray scale and color capability, moderate cost). Since the DIGISPLAY utilizes well understood technologies, it should require less additional development to reach the difficult performance objectives of the VDS application than the other non-CRT dot matrix approaches.

The DIGISPLAY requires moderately high switching voltages (between 50 and 100 volts), high phosphor voltages (between 10 and 20 kv), and a storage target to achieve high brightness in large video displays. At the current stage of development, a 512x512 video-DIGISPLAY has been constructed in a bell jar; it has an active area of 6.4 inches square and utilizes 32 simultaneous writing beams.

In a DIGISPLAY the average spot brightness decreases as the number of resolution elements scanned per frame by each beam increases, due to shortening of the time each beam dwells on each addressed element. The maximum current, per beam, transmitted to the DIGISPLAY phosphor is limited by the output current available from the area cathode, which in turn is limited by the power which can be supplied to the cathode without overheating the device. Therefore, from a practical standpoint, the total integrated current striking the phosphor can be increased only by increasing the number of simultaneously scanning beams.

However, when a "storage" target is added to the DIGISPLAY, brightness enhancement may be achieved by effectively increasing the beam dwell time per element by several orders of magnitude, thus increasing the brightness substantially. Also, since the DIGISPLAY's unique construction already includes an areal electron flood gun, the addition of storage will add little to the cost and complexity of the overall device. The use of a storage target in a

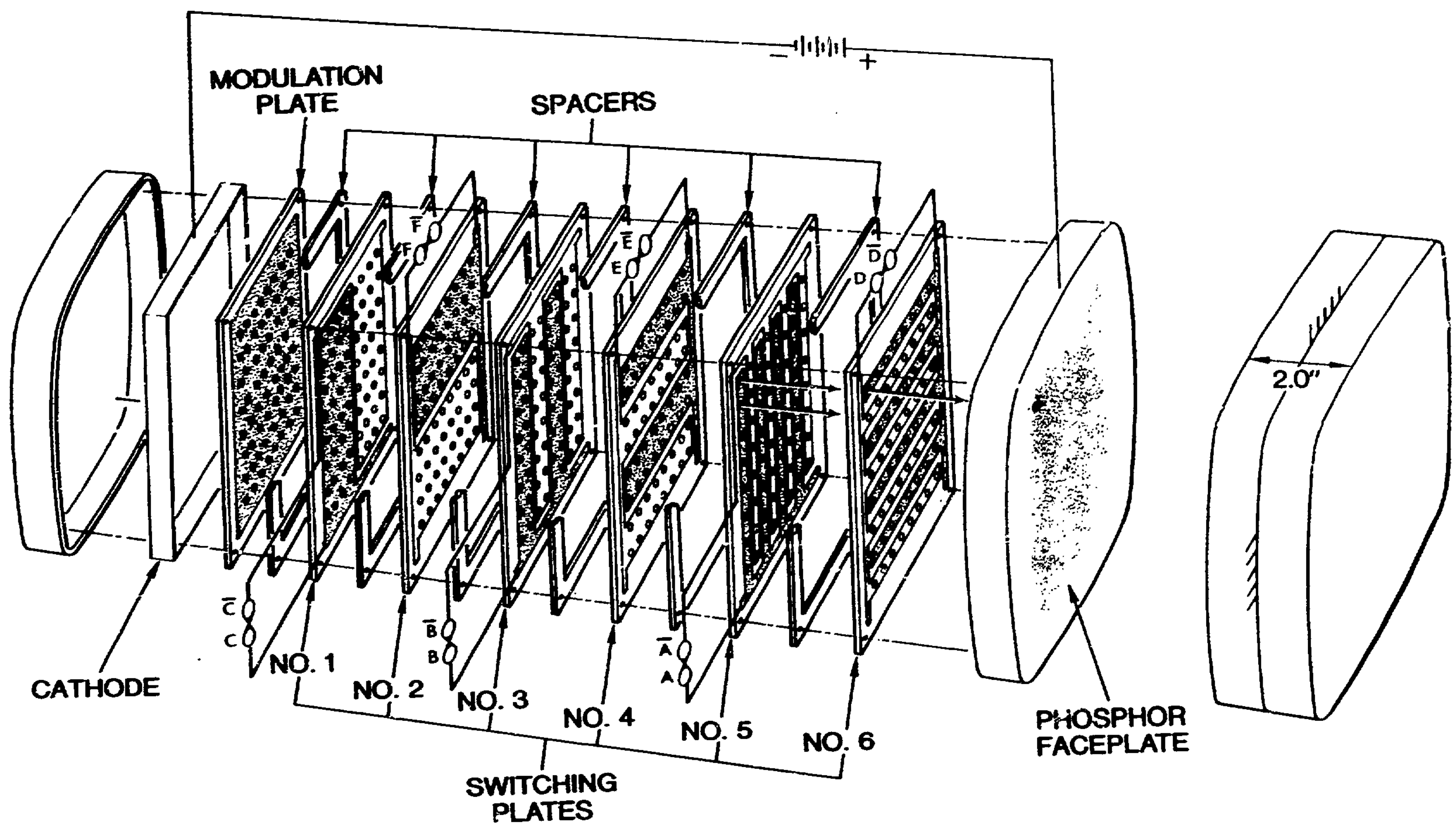

FIGURE 41 TV/GRAPHIC DIGISPLAY PRINCIPLE OF OPERATION

DIGISPLAY also serves to provide greatly improved utilization of the available areal cathode capacity. During the "flood" or view time, which will be discussed later in detail, each "on" element becomes a phosphor-writing beam and the total number of beams is then limited only by the actual number of resolution elements in the display.

Storage is very difficult and expensive to implement in a CRT because of the problems of maintaining linearity and good focus of the writing gun while at the same time adding a flood gun which operates in a defocused condition.

A sketch of a typical storage DIGISPLAY is shown in figure 42. This device can be seen to consist of an area cathode, a series of beam switching plates, a collector plate, a storage target, a contrast enhancement plate (optional), and a phosphor. Both the collector and contrast enhancement plates are merely continuously electroded switching plates and the entire stack, from the output buffer to the contrast enhancement plate, is typically 0.10- to 0.150-inch thick. The storage target itself is merely a metal mesh coated on the electron input side with a dielectric material having good secondary electron emission (SEE) characteristics (yield of unity at 40 volts and yield of 2 - 3 at several hundred volts of primary energy). Simple experiments to date indicate that the screen itself may be replaced by a modified aperture plate coated with SEE material.

The actual method of storage DIGISPLAY operation is discussed below for each of the three required modes - erase, write, and flood:

1) <u>Erase</u> - The switching plates are operated in the "all holes ON" condition with between 0 and 40 volts accelerating potential on the metal storage mesh. The SEE yield is then less than unity, and the surface of the dielectric material on the mesh is charged negative, erasing any information (positive charge) previously written on the mesh. Typical erase times are $<100\ \mu s$. During the erase time, the contrast enhancement plate is biased below cathode potential to prevent the electron beams from striking the phosphor, thus preventing loss of contrast caused by illuminating the phosphor with the erase beams.

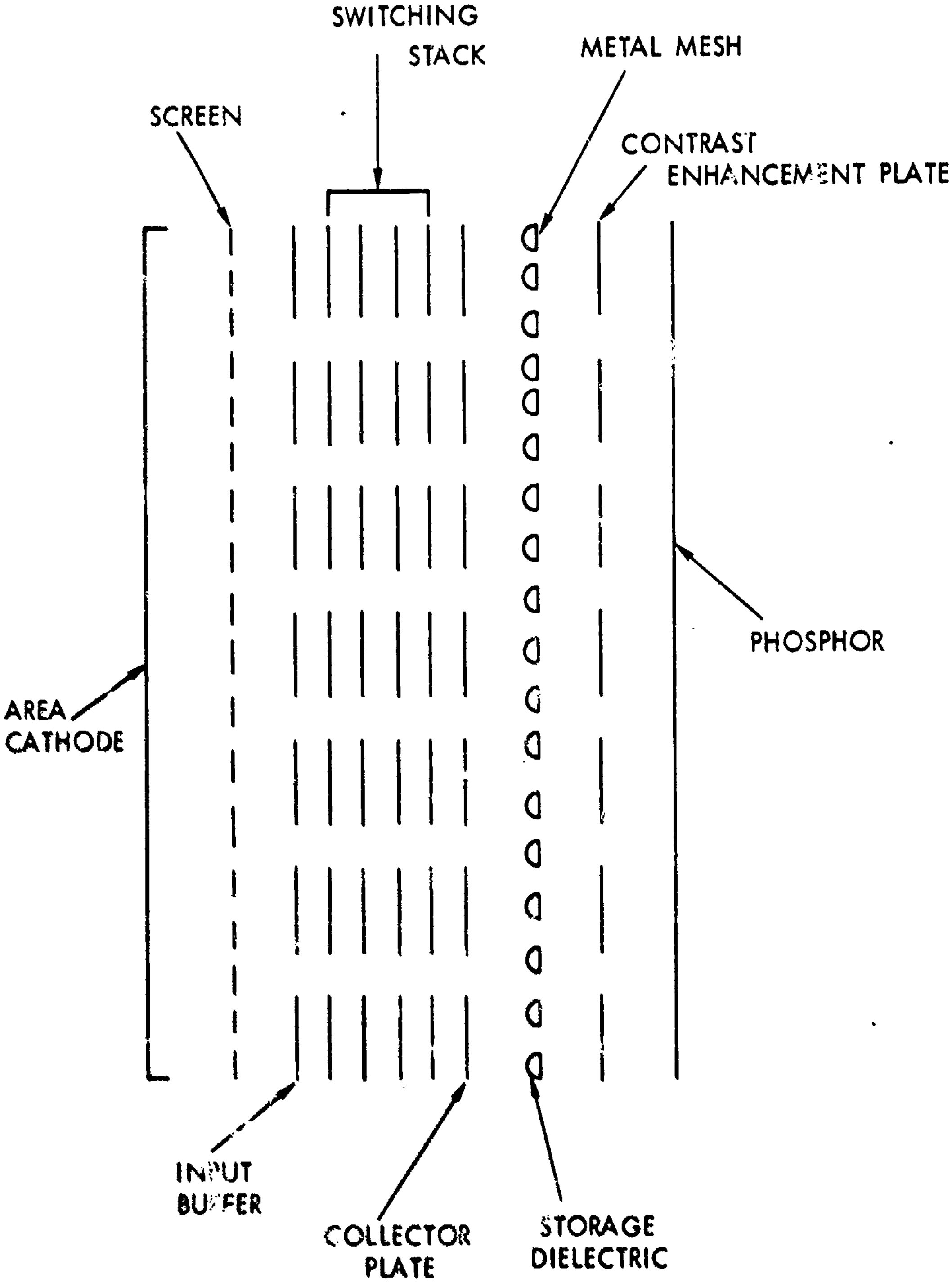

FIGURE 42 TYPICAL STORAGE DIGISPLAY CONFIGURATION (EXPLODED VIEW)

2) Write - In the write time interval, the ESD (Electrostatically Switched DIGISPLAY) plates are scanned through one frame (or one-half frame when interlaced) of information in the same manner as in a nonstorage DIGISPLAY, including modulation to provide gray scale. The metal backing mesh of the storage target is elevated to several hundred volts above cathode potential, so that the scanned and modulated electron beams striking the dielectric layer cause it to charge positive due to the SEE ratio of >1. The secondary electrons generated in writing the information on the storage dielectric material are absorbed on the collector plate, which is held at a potential somewhat above that of the mesh itself. The amount of positive charge thus written on the dielectric surface, for each resolution element, is dependent on the incident beam current and the (write) time. This current is allowed to strike the dielectric. Typical commercially available storage targets require a charge of approximately 1×10^{-13} coulomb to write the target to 80% of full brightness over a 0.0065-inch diameter spot. Therefore, for example, a beam current only 1×10^{-7} amp written for 1 μs is sufficient to provide this charge.

3) Flood (View) - At this point in time, with one frame of information written on the dielectric surface of the storage target, the ESD stack is again switched to "all holes ON", as in the erase mode. However, the metal backing mesh of the storage target is now set at or near cathode potential, such that:

a) Areas which are charged completely positive during the write cycle transmit electrons to the phosphor.

b) Areas which are not positively charged repel electrons back to the collector plate.

c) Areas which are charged less positive than in case (a) due to modulation during writing, transmit fewer electrons than in case (a) and retain the written gray scale.

The length of the flood cycle relative to the erase and write cycle determines the brightness of the display. The length of the flood time is limited by the length of time the stored charge will remain on the dielectric

surface, and by the update time required by system requirements. Typically, storage times of approximately 15 minutes have been demonstrated.

At this point the Erase, Write, and Flood cycle is repeated for the next frame. The storage DIGISPLAY should have the following advantages over a direct view storage CRT:

a) An inherently simpler design with only one gun, no collector mesh, no ion repeller, and no complex collimating system which should result in a lower manufacturing cost.

b) Much smaller in size, lighter in weight, and more rugged construction.

c) Storage time should be inherently longer since ion bombardment should be minimized by the presence of scanning plates.

d) Selective write and erase should be easier to implement.

e) Uniformity and registration are not hampered by off-axis guns.

f) Very fast erase.

g) No screen "flash" during erase, resulting in higher contrast.

h) Plus all the normal advantages of a DIGISPLAY over a CRT, which include:

- Superior registration because the electron beams are physically confined by accurately placed channels in the scanning plates.
- Digital address signal which is directly compatible with a computer interface, resulting in considerable savings in addressing circuitry.
- Random scan capability - unlike the CRT, the time required to switch the beam position in the DIGISPLAY is not dependent on the distance the beam is moved.
- Flat-panel construction - the total depth of the DIGISPLAY is approximately 2 inches.
- Stray-field independence - DIGISPLAY performance is relatively unaffected by stray electric and magnetic fields.
- Multibeam feature - the multibeam feature of the DIGISPLAY offers several advantages over the conventional writing techniques utilizing

only a single beam and is much easier and less expensive to implement than in a CRT. Greater display brightness can be achieved with multiple beam scanning.

The major characteristics of the DIGISPLAY are itemized and discussed below.

- <u>Panel Fabrication</u> - The switching plates are fabricated by a photo etching process to achieve accurate alignment and registration of holes. The complete set of switching plates is assembled and frit sealed together to form a solid glass structure approximately 1/8-inch in thickness. The metal electrode patterns are applied to the switching plates by a vapor deposition technique. This results in a relatively low cost, rugged, flat-panel that can be built in a wide range of sizes and shapes.

- <u>Resolution</u> - The resolution demonstrated to date is 80 holes/inch. However, the plate etching technology can be extended.

- <u>Contrast and Gray Scale</u> - Contrast ratios in excess of 50 to 1 have been demonstrated to date in alphanumeric and video displays. Gray scale is achievable by analog modulation of the electron beam by a control grid. To date, eight shades of gray have been demonstrated in the laboratory.

- <u>Color</u> - Color can be provided in a DIGISPLAY system by use of a two-layer voltage penetration phosphor. These phosphors are less efficient than the monochrome type and the resulting lower screen brightness might not be an attractive tradeoff for the VDS application.

- <u>Brightness</u> - The most serious limitation of a DIGISPLAY system is the limited brightness capability. Screen brightness levels of 350 FL have been demonstrated on alphanumeric displays operating at 8 kv. However, for a large video display requiring a minimum of 1300 FL screen brightness it is necessary to use a storage target to improve the scanning duty cycle and thereby increase the screen brightness.

- **Switching Voltages** - The switching voltages required to achieve good cutoff characteristics vary from 70 to 150 volts, which is incompatible with LSI technology but does permit the utilization of hybrid circuit techniques. The accelerating potential between the decoding stack and the phosphor will be approximately 10 - 15 kv, which requires careful consideration of the shielding design.

- **Power** - The estimated power for a video DIGISPLAY for the VDS application is approximately 190 watts.

- **Scanning Rates** - The switching time for the transition of a decoding plate from an "on" to "off" mode is 0.2 μsec. This permits the achievement of the relatively high video bandwidth of 19 MHz required by the VDS with as few as 10 simultaneous writing beams. However, a greater number may be utilized (approximately 50) to ease the circuit design requirements for each writing beam.

4.7.1 Summary

The DIGISPLAY is a very promising display technique for the VDS application. The most serious limitation is lack of brightness, which can be overcome by utilization of a storage target to improve the scanning duty cycle. One of the main advantages of a DIGISPLAY system is the relatively low parts count required for the total system, because of the efficient implementation of beam position decoding, which has a very favorable impact on system reliability. The size, weight and power requirements are also competitive.

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5.0 EVALUATION OF NON-CRT DISPLAY TECHNIQUES

This section discusses the study methodology used to assess the capabilities of the various advanced non-CRT candidate display techniques and provides the relative rankings of the techniques based on the results of the weighting factor analysis.

5.1 STUDY METHODOLOGY

The study methodology used to select the most promising advanced non-CRT display techniques for application to a VDS for a 1985 era naval attack aircraft is shown in figure 43. Twelve candidate advanced non-CRT display techniques were selected for analysis. The published scientific literature for these techniques was surveyed and analyzed, and the latest technical information regarding present and future performance levels and operational characteristics was solicited from 25 companies which were pursuing research and development efforts in these display technologies. Additional technical information was obtained via telephone conversations and personal visits with some of the leading research workers in the various display fields. This information was analyzed and tradeoff studies were performed to determine how each of the various display techniques could be utilized in a system that could fulfill the VDS design goals. Two weighting factor analyses were performed on each of the advanced non-CRT display techniques, one based on present performance levels (early 1972) and a second based on levels of performance anticipated by the end of 1975. The mean value of the two scores was also computed as a rating guide.

5.2 RELATIVE RANKINGS OF THE NON-CRT DISPLAY TECHNIQUES

The results of the weighting factor analysis is shown in table 20, and the complete scoring sheets are contained in the Appendix. The display techniques are arranged in four descending groups based on the mean scores obtained from the analysis. Group 1 consists of the DIGISPLAY and liquid crystal techniques which were almost equal. They scored approximately 20 percent higher than the Group 2 techniques (LED's, ferroelectric, and ac plasma) which are rated about equal. The Group 3 techniques, which include oil film, laser and electroluminescence, rated approximately equal and 10 percent lower than the techniques in Group 2. The Group 4 techniques (magneto-optic, dc plasma, deformographic, and cathodochromic) were rated about equal in the evaluation but approximately 20 percent lower than the techniques in Group 3.

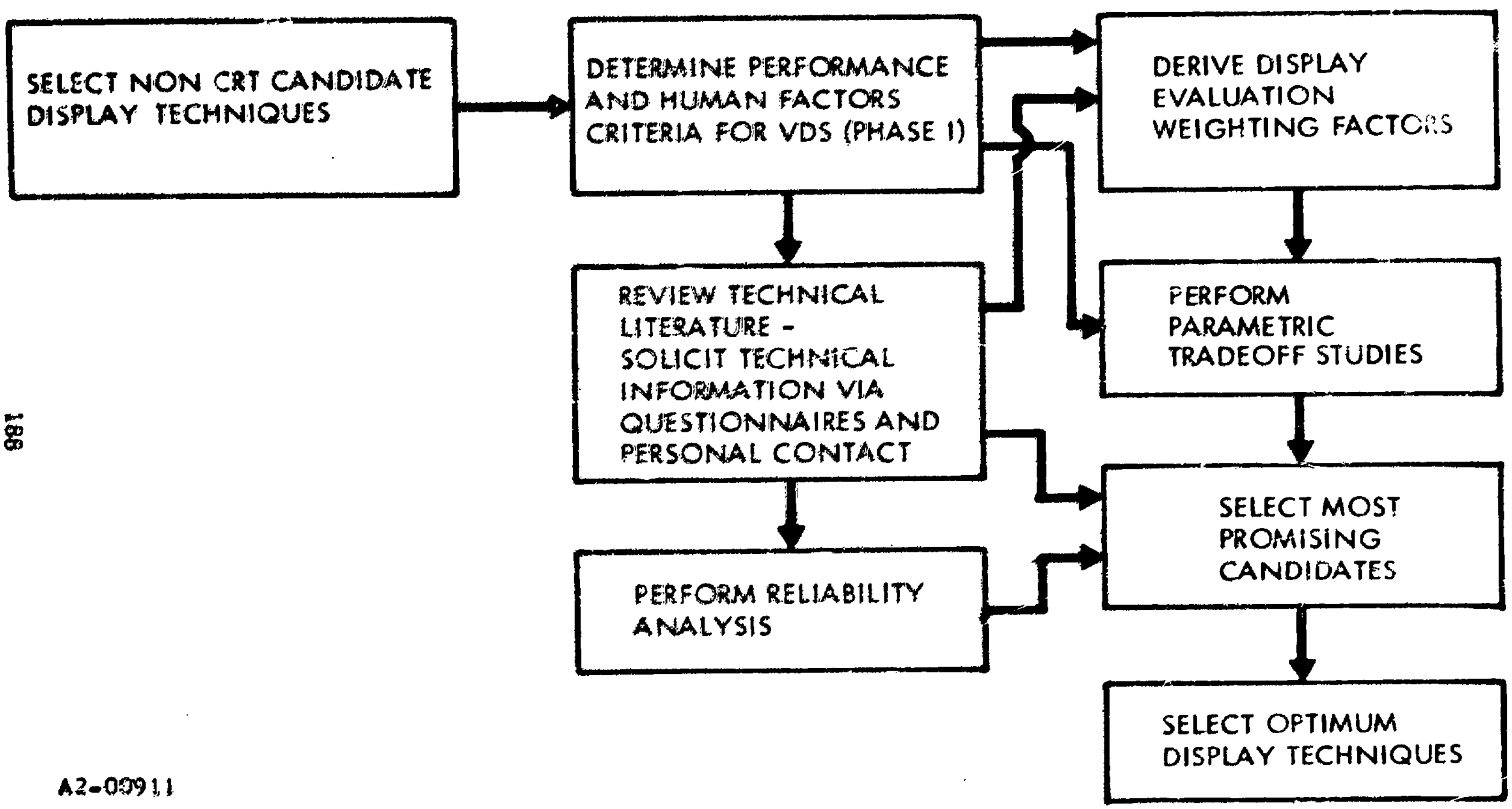

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FIGURE 43 VDS DISPLAY TECHNIQUES TRADEOFF STUDY METHODOLOGY

TABLE 20 RELATIVE RANKING OF ADVANCED NON-CRT DISPLAY TECHNIQUES

	Present Performance	Future Performance	Average Score
Group 1			
DIGISPLAY	39	90	65
Liquid Crystal	45	83	64
Group 2			
Light Emitting Diodes	38	68	53
Ferroelectric	27	76	51
AC Plasma	32	68	50
Group 3			
Laser	39	54	47
Electroluminescence	33	60	47
Oil Film	34	57	46
Group 4			
Magneto-Optic	25	52	39
DC Plasma	23	53	38
Deformographic	25	50	37
Cathodochromic	15	53	34

The results of the weighting factor analysis indicated that the five advanced non-CRT display techniques in Groups 1 and 2, which include DIGISPLAY liquid crystal, ac plasma, LED's, and ferroelectric offer the greatest potential of fulfilling the design and performance goals that were established for the 1985 era VDS. These five display techniques are therefore considered to be the most attractive candidates for the VDS application. Tables 21 and 22 are listings of the comparative weighting factor values for the display techniques from groups 1 and 2, respectively. These tables indicated how the techniques were rated relative to each other on an individual parameter basis. A detailed systems reliability analysis was performed (see section 5) for all five of the display techniques to determine the MTBF figures for each technique when operating with all of the components required in the total VDS system for operation with TV, FLIR, and RADAR systems carried on board the aircraft.

5.3 STATUS SUMMARY OF NON-CRT DISPLAY TECHNIQUES

A brief summary of the status of each advanced non-CRT display technique is presented with comments regarding the relative rankings of the display techniques.

GROUP 1 - DISPLAY TECHNIQUES - These display techniques are considered to have the highest potential of fulfilling the performance goals of a 1930 era VDS. They are rated about 20 percent higher than the techniques in Group 2.

DIGISPLAY - The DIGISPLAY technique was rated as one of the two techniques with the highest potential of fulfilling the VDS design goals. Its main advantage is a relatively simple addressing technique which requires a relatively low number of circuit elements to implement. The reliability analysis has shown that it has the highest potential reliability from a systems viewpoint. It scored moderately high in all of the important display performance parameters. Its most serious disadvantage is lack of brightness which probably can be overcome by use of a storage technique. The switching voltages are relatively high precluding the use of LSI technology at this time. However, hybrid circuit techniques can be implemented. The size, weight, and power are also competitive.

LIQUID CRYSTALS - The liquid crystal display is one of the most promising techniques for satisfying the performance requirements of the vertical display system. Its major advantages are low switching voltages, low power and low

TABLE 21 COMPARISON OF WEIGHTING EVALUATION PARAMETERS FOR GROUP 1 DISPLAY TECHNIQUES

			DIGISPLAY		LIQUID CRYSTAL	
WT	DISPLAY PARAMETER	DESIGN GOAL	PERFORMANCE PRESENT/FUTURE	COMB. WT'G.	PERFORMANCE PRESENT/FUTURE	COMB. WT'G.
12	Reliability MTBF	2000 hrs	1500 hrs/5000	7.6	1000 hrs/2700	4.2
12	Scanning Rate	20 MHz	5 MHz/20	7.5	5 MHz/20	7.5
8	Grey Scale	10 Shades	8/10	6.0	8/10	6.0
7	Brightness	1300 F-L min.	350 F-L/1300	0.1	2500 F-L/2500	7.0
5	Uniformity	±10%	±12%/10	4.5	±20%/12	2.0
5	Resolution	100 dots/inch	80/100	4.0	100/100	5.0
5	Maintainability	1000 hrs between adjustments	400 hrs/600	2.5	400 hrs/600	2.5
5	Production Cost	<$50K	<$75K/<$50K	3.5	<$100K/<$50K	3.0
5	Design Complexity	Low	--	3.5	--	1.5
5	Production Feasibility	Good	--	3.5	--	1.5
4	Screen Size	9.5 in.sq. 8.93×10^5	6 in.sq./10	3.0	--/10	2.0
4	Volume	<1.5 ft^3	1.5 ft^3/0.5	3.0	1.5 ft^3/0.5	3.0
3	Spot Size	5 mils	6.25 mils/5	2.5	5 mils/5	3.0
3	Weight	<100 lbs	75 lbs/50	2.6	50 lbs/50	3.0
3	Average Power	<300 watts	400 watts/160	0.9	100 watts/<100	3.0

TABLE 21 COMPARISON OF WEIGHTING EVALUATION PARAMETERS FOR GROUP 1 DISPLAY TECHNIQUES (CONT'D)

			DIGISPLAY		LIQUID CRYSTAL	
WT	DISPLAY PARAMETER	DESIGN GOAL	PERFORMANCE PRESENT/FUTURE	COMB. WT'G.	PERFORMANCE PRESENT/FUTURE	COMB. WT'G.
2	Contrast Ratio	23 - 1	23/23	2.0	23/23	2.0
2	Temperature and Humidity	MIL-E-5400	No/Yes	1.0	No/Maybe	0.5
2	Shock	MIL-E-5400	No/Yes	1.0	No/Yes	1.0
2	Vibration	MIL-E-5400	No/Yes	1.0	No/Yes	1.0
2	EMI and RFI	MIL-E-5400	No/Yes	1.0	No/Yes	1.0
1	Color	2 or more	2/2	1.0	2/2	1.0
1	Storage	2 minutes	30 sec/30	1.0	>30 min/>30 min	1.0
1	Form Factor	2 packages	2/2	1.0	2/2	1.0
1	Peak Power		300 watts/250	1.0	<1 KW/<1	1.0
		TOTAL	DIGISPLAY	65	LIQUID CRYSTAL	64

TABLE 22 COMPARISON OF WEIGHTING EVALUATION PARAMETERS FOR GROUP 2 DISPLAY TECHNIQUES

WF	DISPLAY PARAMETER	DESIGN GOAL	LED		A.C. PLASMA		FERROELECTRIC	
			PERFORMANCE PRESENT/FUTURE	COMB. WT'G.	PERFORMANCE PRESENT/FUTURE	COMB. WT'G.	PERFORMANCE PRESENT/FUTURE	COMB. WT'G.
12	Reliability MTBF	500 hrs	2780/2780	6.4	1000/1000	2.0	800/100	0
12	Scanning Rate	20 MHz	5 MHz/20	7.5	4 MHz/20	7.2	20/20	12.0
8	Gray Scale	10 Shades	10/10	8.0	4/6	-2.0	2/10	0
7	Brightness	1300 F-L min.	EQ 100/EQ 1200	-2.3	300/1000	-0.9	2500/2500	7.0
5	Uniformity	±10%	±15%/12	3.3	10%/10%	5.0	±24%/12%	1.0
5	Resolution	100 dots/inch	60/100	3.0	80/100	4.0	60/100	2.5
5	Maintainability	1000 hrs between adjustments	400 hrs/600	2.5	400 hrs/600	2.5	400 hrs/600	2.5
5	Production Cost	<$50K	100K/100K	2.0	50K/50K	4.0	125K/100K	1.5
5	Design Complexity	Low	--	2.0	--	4.0	--	1.0
5	Production Feasibility	Good	--	2.0	--	4.0	--	1.0
4	Screen Size	9.5 in.sq.	6 in.sq/10 in.	3.0	6 in.sq/10 in.	3.0	0/10 in.	2.0
4	Volume	<1.5 ft^3	1.0 ft^3/1.0	3.0	1.5 ft^3/1.0	2.5	1.5 ft^3/0.5 ft^3	3.0
3	Spot Size	5 mils	8 mils/5	1.8	6.25 mils/5	2.5	5 mils/5	3.0
3	Weight	<100 lbs.	75 lbs/75	2.2	75 lbs/50	2.6	75 lbs/50	2.6
3	Average Power	< 300 watts	2000 watts/1000	-3.0	500 watts/400	0	100 watts/100	3.0

TABLE 22 COMPARISON OF WEIGHTING EVALUATION PARAMETERS FOR GROUP 2 DISPLAY TECHNIQUES

WF	DISPLAY PARAMETER	DESIGN GOAL	LED PERFORMANCE PRESENT/FUTURE	LED COMB. WT'G.	A.C. PLASMA PERFORMANCE PRESENT/FUTURE	A.C. PLASMA COMB. WT'G.	FERROELECTRIC PERFORMANCE PRESENT/FUTURE	FERROELECTRIC COMB. WT'G.
2	Contrast Ratio	23 - 1	23/23	2.0	23/23	2.0	20/23	1.8
2	Temperature and Humidity	MIL-E-5400	Yes/Yes	2.0	No/Yes	1.0	No/Yes	1.0
2	Shock	MIL-E-5400	Yes/Yes	2.0	No/Yes	1.0	No/Yes	1.0
2	Vibration	MIL-E-5400	Yes/Yes	2.0	No/Yes	1.0	No/Yes	1.0
2	EMI and RFI	MIL-E-5400	Yes/Yes	2.0	No/Yes	1.0	No/Yes	1.0
1	Color	2 or more	2/2	1.0	2/2	1.0	1/2	0.5
1	Storage	2 minutes	No/No	0	>2 min/2	1.0	>30 min/30	1.0
1	Form Factor	2 packages	2/2	1.0	2/2	1.0	2/2	1.0
1	Peak Power		>1 KW/>1 KW	0	>1 KW/1	0.5	<1 KW/1	1.0
			LED TOTAL	53	A.C. PLASMA TOTAL	50	FERROELECTRIC TOTAL	51

cost, electrical compatibility with MOS driver circuitry, high resolution, high brightness and good contrast even in direct sunlight. The main disadvantages are half select and cross talk problems, slow response and decay times, complex addressing circuitry, limited temperature range, differential aging and high sensitivity to fabrication tolerances. Its reliability is limited primarily by the complex matrix addressing circuitry required. The ultimate feasibility of the liquid crystal display for the VDS application will depend on the development of an adequate scanning or multiplexing scheme to address the display matrix. It is anticipated that the addressing problem can be solved by the use of integrated circuitry and mass-fabrication techniques with the possible construction of a large size display by the stacking of a number of submatrix structures.

GROUP 2 - DISPLAY TECHNIQUES - The display techniques in this group are considered to be approximately 20 percent lower in potential for the VDS application than the displays in Group 1. However a dramatic improvement in performance by any one technique could make it the most attractive candidate.

LIGHT EMITTING DIODES - Light emitting diodes are presently unattractive because of low conversion efficiency which would require the use of more than 1 kw input power and present serious thermal design problems. However, the physics problems are well understood, and improvement in conversion efficiency by over an order of magnitude is anticipated. The LED's are rugged and long lived; however because low brightness will probably necessitate the use of a storage element with each element in the display, or the use of a line-at-a-time addressing technique. Either of these design possibilities has an unfavorable impact on system reliability. The cost for a large video display is presently prohibitive; however, there are favorable predictions for the future. Advances in LED technology will undoubtedly be made but perhaps not fast enough to meet the performance requirements of a 1980 era VDS.

FERROELECTRIC CERAMICS - The ferroelectric bismuth titanate display has the advantage of being a flat panel device with good resolution, high brightness, adequate contrast ratio, low power, inherent storage and minimum fatigue problems. The disadvantages are compositional and geometrical tolerance requirements for the crystal, fabrication and assembly difficulties with the stacked bar per line approach, high drive voltages, and line-at-a-time addressing requirements for video rates with its associated complex circuitry. Although the device is still in the early development stage, the ferroelectric ceramic display received a relatively high rating in the evaluation scores due to the excellent optical performance anticipated and the very low size, weight and power characteristics.

AC PLASMA - The ac plasma display technique is in a fairly advanced state of development. Its main limitations are lack of brightness and gray scale and relatively slow switching times which require line-at-a-time addressing. The circuit complexity required to achieve more gray scale capability and still retain memory is a formidable task, and the additional circuitry required for line-at-a-time addressing has a degrading effect on system reliability. The power requirement is relatively high for a large video display with high brightness requirements, and the higher switching voltages required preclude the use of LSI technology at this time, but hybrid circuit techniques may be implemented.

GROUP 3 - DISPLAY TECHNIQUES - The display techniques in this group are considered to have a 10 percent lower potential of fulfilling the design goal requirements of the VDS than the techniques of Group 2. However, a dramatic improvement in the performance of any of these techniques could move them into a category of more serious contention.

LASER - The scanning laser display technique can satisfy most of the performance requirements for the 1980 VDS applications. Its most serious deficiency is the conversion efficiency from electrical input to laser light output. The efficiency is presently so low that approximately 10 kw electrical input is required to achieve the brightness requirements of the VDS. This also presents systems cooling design problems. The system also has a large volume and the ruggedization required for the aircraft cockpit environment presents

a design problem. However, with improved conversion efficiencies the laser could become a more serious contender.

ELECTROLUMINESCENT - Electroluminescent displays have a long history of development but still suffer from a lack of brightness due to low conversion efficiencies and relatively short life. Attempts to increase brightness lead to even shorter lifetimes. The relatively slow switching times require line-at-a-time addressing for the VDS application. This display is inherently low cost, rugged and compact but requires relatively high switching voltages which precludes the use of LSI technology. A large improvement in light output and conversion efficiency would be required to make this display technique attractive for the VDS application.

OIL FILM - The most significant advantage of the oil film technique is its present capability of displaying video images at TV rates with good resolution, high brightness and contrast ratio, good gray scale and demonstrated color presentation. Its major disadvantages are large size, weight and power requirements, relatively high cost and anticipated difficulties in producing a mil spec qualified system for cockpit application. The oil film display received only a moderate rating in the display techniques evaluation primarily because of the stringent size, weight, and power limitations established for the vertical display system.

GROUP 4 - DISPLAY TECHNIQUES - The display techniques in this group are considered to be approximately 20 percent lower in potential for the VDS application than the Group 3 displays. It is doubtful that enough improvement could be made in these techniques in the time available to seriously consider their use in the 1980 VDS application.

MAGNETO-OPTIC FILM - Although the magneto-optic display technique has the advantages of high brightness, good resolution and contrast, inherent memory and low switching voltages, it has several significant disadvantages such as a high triggering current, narrow viewing angle, bulky optical system, questionable gray shade capability, and requires 1/3 line-at-a-time addressing for video rates. At the present time, the driver electronics limit the writing speed and represent the largest contributor to the size, weight,

power and cost of the display system. The device received a low rating for the VDS application primarily because of the size and power requirements and the limited reliability of complex matrix addressing circuitry.

DC PLASMA - The dc plasma has a very serious brightness deficiency for the VDS application. It also lacks the memory capability of the ac plasma and requires complex addressing circuitry. However it may be easier to satisfy the gray scale requirements. The panel lifetime may be low due to the use of internal electrodes. Because of the relatively high power requirements, serious design problems, and very limited number of attractive features, the dc plasma is not considered to have high potential for the VDS application.

DEFORMOGRAPHIC FILM - The deformographic display tube has the advantages of high brightness, excellent resolution, inherent storage, and good contrast and gray scale when operated in the storage mode. Its disadvantages include nonuniformity problems, large size of complete unit (projection optical system), short lifetime, and vulnerability of the schlieren optics to vibrational misalignment in a cockpit application. The main performance characteristic which must be improved for application to the vertical display system is the relatively long write-erase cycle time. The DFG tube received a relatively low rating for this application primarily because of the large volume requirement, limited reliability, and the anticipated difficulties in achieving video rate operation with adequate contrast ratio.

CATHODOCHROMIC - The cathodochromic display tube is a relatively simple, inexpensive CRT-type device suitable for applications in which long storage times are desirable and slow address rates do not present a problem. The very slow address and erase cycle times and the anticipated short lifetime rule out the consideration of this display technique at the present time.

6.0 SYSTEM RELIABILITY ANALYSIS

A tradeoff study was performed to determine predicted system reliability for the five most promising display techniques. The candidate displays included in the study were 1) light emitting diodes, 2) DIGISPLAY, 3) liquid crystal, 4) plasma, and 5) ferroelectric.

6.1 ANALYSIS PROCEDURE

For this analysis the equipment required to implement each mode of operation was identified and considered to operate in a series configurations such that a failure of a single equipment in a particular mode constituted a system failure. Each equipment in turn was further broken down to its individual circuit elements and the overall system failure rate was calculated by summing the failure rates for each of the circuit elements, i.e.,

$$\text{Equipment failure rate} = \sum_{i=1}^{k} n_i \lambda_i$$

where

n_i = total number of discrete circuit element of one type

λ_i = random failure rate of the discrete circuit element (expressed in terms of failure per million operating hours)

k = number of different discrete circuit elements

The MTBF for each equipment and a total system MTBF was calculated by taking the reciprocal of the total failure rates.

6.2 FAILURE RATE DATA

Circuit element failure rates were derived where possible from industry established and recognized sources such as MIL-HDBK-217A. In cases where the handbook did not contain failure rate data for the part type, Northrop internal test data and other sources such as Farada were utilized.

In the case of the display devices themselves very little statistically significant data is available to establish random failure rates due to the fact that they are in a very early development phase. The majority of devices have not yet been assembled to yield the design goal of a 1000 by 1000 matrix. Where possible an attempt was made to predict a more meaningful estimate of failure rate by extension of current technologies. This approach was possible in the case of DIGISPLAY and light emitting diodes. The DIGISPLAY failure rate was estimated on the basis of extension of failure rates published in Farada for storage type CRT's currently in use in computer terminals, oscilloscopes, radar displays, etc. The LED rates were based upon extension of technologies utilized in semiconductor fabrication, particularly those techniques applicable to Large Scale Integration (LSI). The failure rates utilized for the remaining display devices should be recognized as being of low confidence in respect to their absolute values because of the many unknowns in the fabrication and assembly processes, but as will be shown later these device failure rates have a low order impact on overall system reliability. The predominant source of high system failure rates is the electronics associated with the display devices. The underlying reason for this conclusion is the extreme complexity of the modulation and drive circuitry, particularly with respect to the devices that due to slow response time or lack of brightness require simultaneous addressing and modulation, line-at-a-time. In addition to the complexity factor, achievement of low failure rates for this circuitry is further inhibited by the nature of the circuits themselves. The modulation and select circuity for the plasma and ferroelectric display techniques require relatively high voltage levels and preclude application of LSI technology in this area. Instead hybrid circuitry consisting of bipolar semiconductor, thick film devices as well as discrete components is dictated. The DIGISPLAY also requires high voltage modulation and select circuitry, but due to its relatively fast response time overall circuit complexity is greatly reduced through digital addressing.

6.3 SYSTEM OPERATIONAL MODES

In addition to calculating system failure rates in terms of the five candidate display devices, three system modes of operation were investigated in ascending order of overall system complexity. These modes are shown in

figure 44 and include the 1) TV mode, 2) the FLIR mode, and 3) radar mode. The reliability flow diagrams are not intended to illustrate a functional signal flow diagram, but are utilized to indicate the various items of equipment required to implement a particular mode of operation. As was stated previously, these items of equipment are considered in the sense that a failure of any equipment would result in a system failure. The TV mode is illustrative of system operation utilizing only that equipment required for real time TV video presentation on the display device without other display symbology. The FLIR mode is illustrative of system operation in which scan conversion of the IR data is required prior to video presentation, but again operation without other display symbology is considered. The final RADAR mode is illustrative of system operation with full system capability and requiring all items of equipment.

6.4 DISPLAY ELECTRONICS

Since the display and display electronics are common to all modes of operation the details of this circuitry and its impact on overall system reliability will be discussed first.

The five candidate devices selected for detailed study can be broken down into two main categories based upon their response time required to produce full design goal brightness. Four of the devices plasma, liquid crystal, LED and ferroelectric being either relatively slow in response time or low in brightness require a modulation scheme in which one complete horizontal line in the matrix must be simultaneously modulated in order to achieve video rates compatible with the design goal of 30 frames per second. The DIGISPLAY on the other hand has very fast response on the order of 0.5 seconds. With this favorable response time it is possible to achieve the above video rates with far less complex circuitry (in terms of overall parts count) through multiplexing of modulation - drivers and matrix select circuit elements.

The effects of these differences in response time on circuit complexity are shown in figures 45 and 46. It will be noted that for the DIGISPLAY that the scanning and select circuitry can be implemented using 100 sample and hold devices, 50 modulation elements and 90 scan select circuits.

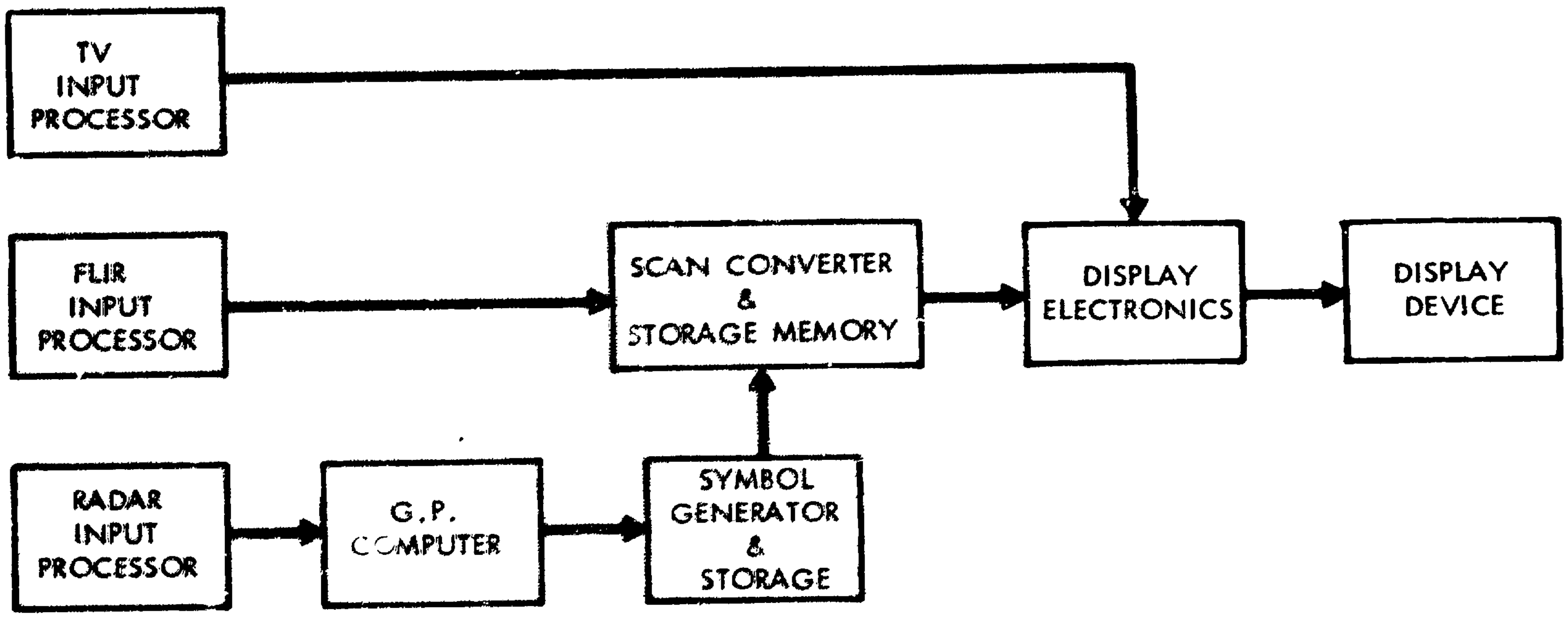

FIGURE 44 RELIABILITY FLOW DIAGRAM

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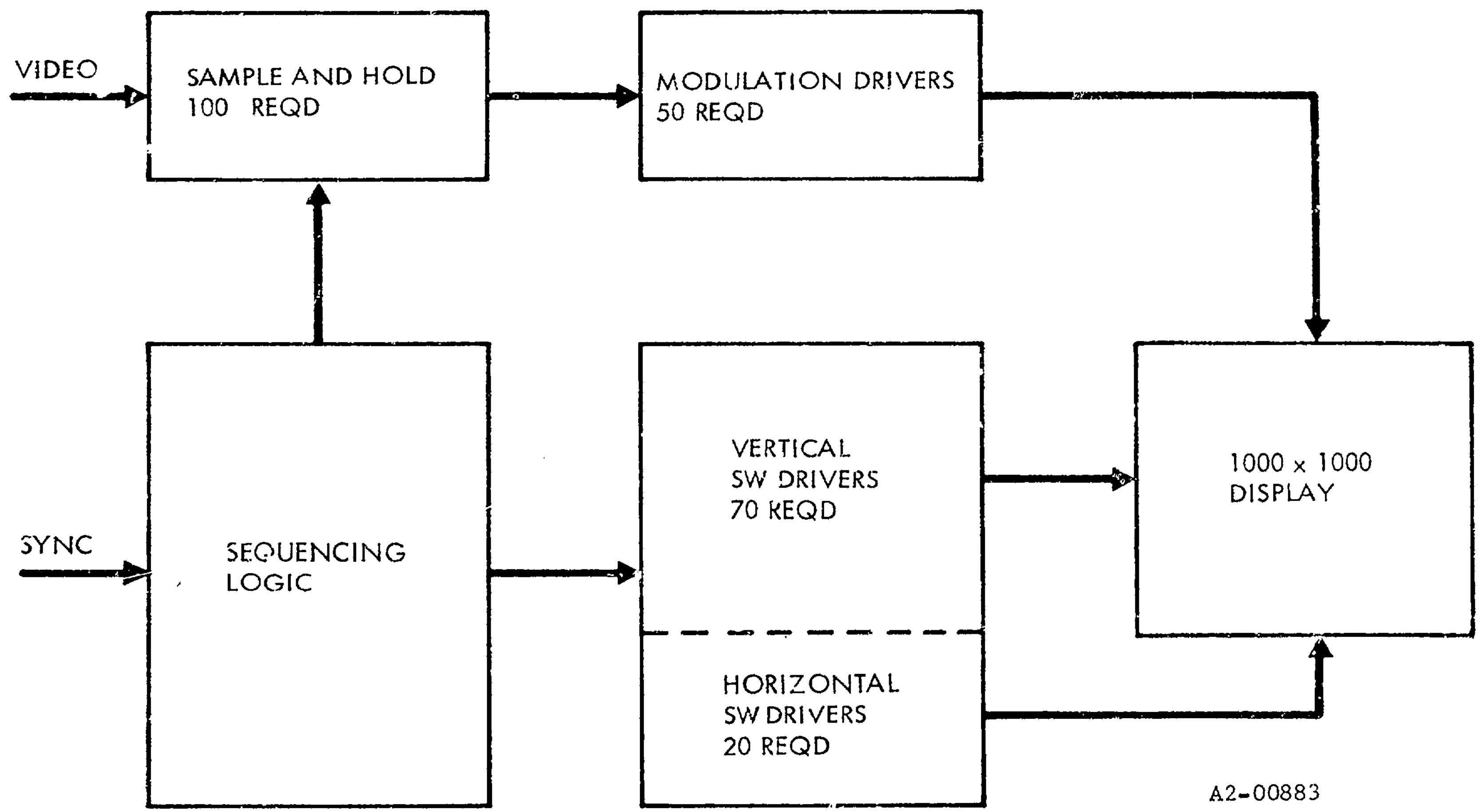


FIGURE 45 DIGISPLAY DISPLAY ELECTRONICS

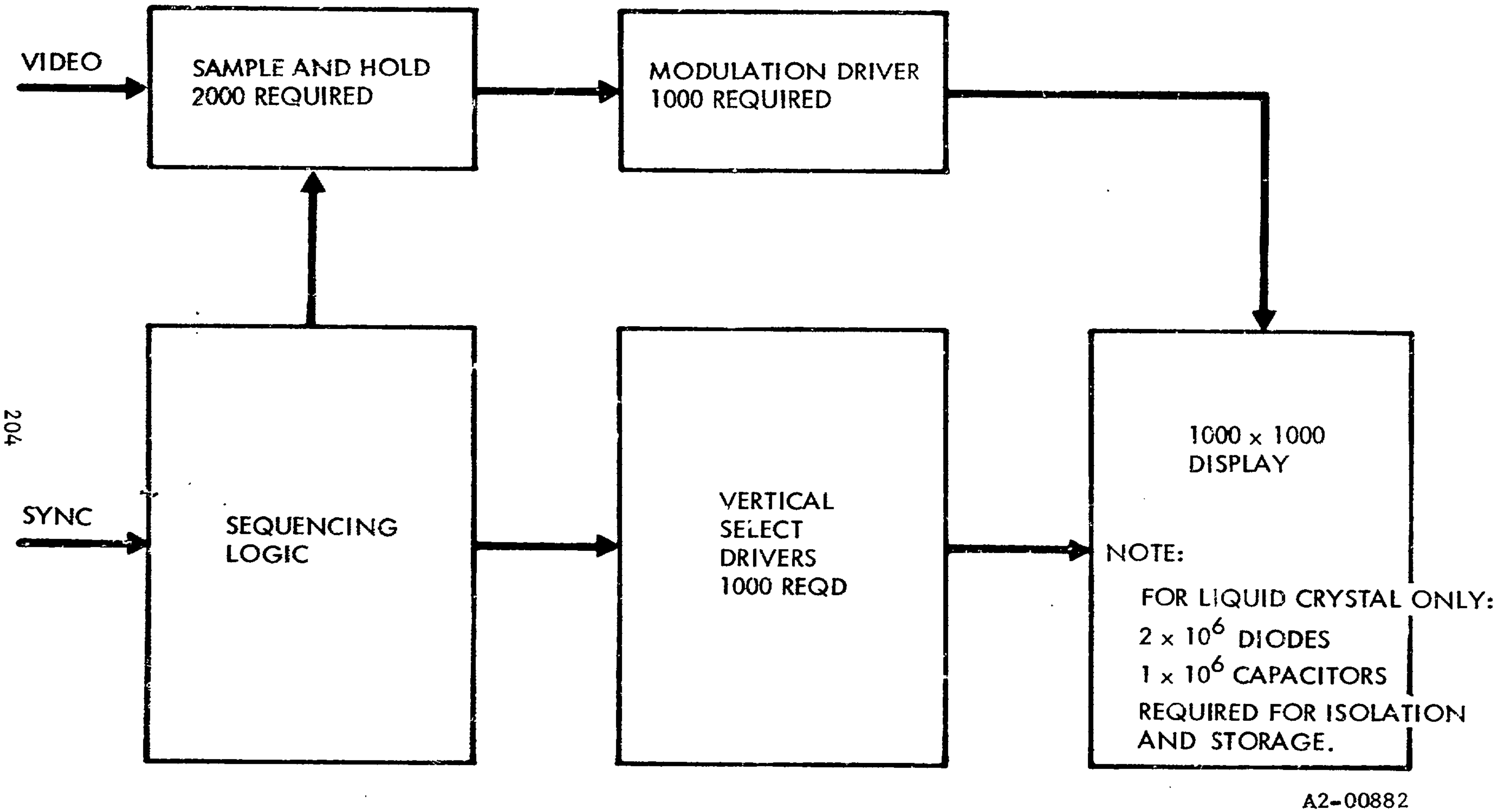


FIGURE 46 LINE-AT-A-TIME DISPLAY ELECTRONICS
(Liquid crystal, ferroelectric, LED, and plasma)

On the other hand for the other four candidate displays 2000 sample and hold devices, 1000 modulation elements and 1000 scan select circuits are required. This represents a full order of magnitude more complexity for the line-at-a time devices than for the DIGISPLAY. As will be shown later this complexity factor is a major deterrent to the achievement of the design goal of 2000 hours MTBF for the overall system particularly with regard to the plasma and ferroelectric displays.

6.4.1 Circuit Implementation

Ideally with the levels of circuit complexity indicated by figures 45 and 46 it would be desirable to utilize large scale integration of circuit elements to reduce component part failure rates. LSI circuitry is desirable from the reliability standpoint because of advantages to be gained from batch processing in device fabrication, reduction of assembly and soldering operations in the equipment manufacturing process, and simplification through reduction of circuit interconnection and electrical connections required. However, due to the relatively high voltage levels required of the modulation and select circuitry for the Plasma, Ferroelectric and DIGISPLAY this approach does not appear feasible for anything approaching a 100 percent LSI design. In the light of the high voltage restriction it is anticipated that implementation of the modulation and select circuit would involve a hybrid approach utilizing a combination of conventional hybrid and bipolar discrete devices in combination with an LSI approach for logic and sample and hold circuits. Two cases were considered in the analysis. The first using totally hybrid circuitry is illustrative of currently available circuit elements, and in the tables that follow is identified as "Hybrid Technology". The second implementation, identified as "LSI Technology", utilizes LSI techniques to the maximum extent possible and is illustrative of the level of reliability that could be achieved in the 1975 time frame.

The circuitry for the LED and liquid crystal displays inherently operate at lower voltage levels. It is anticipated that total LSI would be utilized throughout in the implementation of this circuitry.

6.4.2 Analysis Results

The result of the reliability analysis for the display and display electronics is shown in Table 23 . As can be seen from these results the circuit complexity required for the plasma, ferroelectric, LED, and liquid crystal displays makes a predominate contribution to the overall failure rate of the display electronics. Also, it should be noted that even with the application of LSI where possible, the failure rate of the display electronics is still a most significant contribution of the overall failure rate.

6.5 OTHER SYSTEM ELECTRONICS

The results of the analysis for other items of equipment required to implement the selected modes of system operation is shown in Table 24. These equipments, with the exception of the TV processor, would be fabricated utilizing MOS/LSI to achieve maximum reliability.

6.6 TOTAL SYSTEM RELIABILITY

Tables 25, 26, 27, and 28 present the total system failure rates and MTBF's after combining the rates derived for the various display devices and other equipment required for each operational mode. Tables 25 and 26 summarize the failure rates for those displays in which a total hybrid implementation of the display electronics was considered. As can be seen, the only display device capable of meeting the design goal of 2000 hours for the fully implemented RADAR mode of operation is the DIGISPLAY. The basic reason for the poor performance of the other devices is the complexity of the circuitry and the requirement for these devices to operate at voltage levels that are not amenable to currently available or projected large scale integration techniques. The LED and liquid crystal devices do not appear in these tables because it is anticipated that their driving electronics would be based on LSI techniques.

Tables 27 and 28 present the failure rates and MTBF based upon utilization of LSI circuit techniques in those circuits that appear compatible with this approach i.e., sample and hold circuits, logic and sequencing circuits and low level modulation circuitry. As can be seen from the tables, utilizing these techniques does improve the overall system reliability for the

TABLE 23 FAILURE RATES

DISPLAY AND DISPLAY ELECTRONICS

DISPLAY DEVICE	F/R (p.p.m.)	HYBRID TECH. ELECTRONICS F/R (p.p.m.)	LSI TECH. ELECTRONICS F/R (p.p.m.)	TOTAL HYBRID F/R (p.p.m.)	TOTAL LSI F/R (p.p.m.)
DIGISPLAY	100	106	50	206	150
PLASMA	40	860	512	900	552
LIQUID CRYSTAL	50	-	445	-	495
L.E.D.	40	-	295	-	335
FERROELECTRIC	50	860	512	910	562

TABLE 24 SYSTEM EQUIPMENT FAILURE RATES
(EXCLUDING DISPLAY AND DISPLAY ELECTRONICS)

ITEM OF EQUIPMENT	OPERATIONAL MODES TV F/R (p.p.m.)	FLIR F/R (p.p.m.)	RADAR F/R (p.p.m.)
TV INPUT PROCESSOR	25	-	-
FLIR INPUT PROCESSOR	-	3	-
RADAR INPUT PROCESSOR	-	-	3
G.P. COMPUTER	-	-	160
SYMBOL GENERATOR	-	-	3
SCAN CONVERTER	-	80	80
TOTALS	25	83	246

TABLE 25 TOTAL SYSTEM FAILURE RATES

HYBRID TECHNOLOGY

DISPLAY TYPE	DISPLAY & DISPLAY ELTN. F/R (p.p.m.)	OPERATIONAL MODE		
		TV	FLIR	RADAR
		TOTAL F/R (p.p.m.)	TOTAL F/R (p.p.m.)	TOTAL F/R (p.p.m.)
DIGISPLAY	206	231	289	452
PLASMA	900	925	983	1146
FERROELECTRIC	910	935	993	1156

TABLE 26 TOTAL SYSTEM MTBF

HYBRID TECHNOLOGY

DISPLAY TYPE	OPERATIONAL MODE		
	TV MTBF (HOURS)	FLIR MTBF (HOURS)	RADAR MTBF (HOURS)
DIGISPLAY	4330	3640	2210
PLASMA	1080	1020	870
FERROELECTRIC	1070	1010	865

TABLE 27 TOTAL SYSTEM FAILURE RATES

LSI TECHNOLOGY

DISPLAY TYPE	DDISPLAY & DISPLAY ELTN. F/R (p.p.m.)	OPERATIONAL MODE		
		TV	FLIR	RADAR
		TOTAL F/R (p.p.m.)	TOTAL F/R (p.p.m.)	TOTAL F/R (p.p.m.)
DIGISPLAY	150	175	433	396
PLASMA	552	577	635	798
LIQUID CRYSTAL	495	520	578	741
L.E.D.	335	360	418	581
FERROELECTRIC	562	587	645	808

TABLE 28 TOTAL SYSTEM MTBF

LSI TECHNOLOGY

DISPLAY TYPE	OPERATIONAL MODE		
	TV MTBF (HOURS)	FLIR MTBF (HOURS)	RADAR MTBF (HOURS)
DIGISPLAY	5700	2300	2530
PLASMA	1730	1570	1250
LIQUID CRYSTAL	1920	1730	1350
L.E.D.	2780	2390	1720
FERROELECTRIC	1710	1550	1230

line-at-a-time device, only the LED display can be co sidered as having potential to meet the design goal system reliability.

6.7 ALTERNATE APPROACH FOR LIQUID CRYSTAL ELECTRONICS

If further development in liquid crystal technology allows for faster response time to reach design goal brightness, a further simplification of driving electronics could be achieved. For the purposes of a comparative analysis, an increase of response time compatible with simultaneous addressing of 10 beams as opposed to 1000 in the previous analysis was considered. The major impact of this approach was to reduce the required quantity of sample and hold devices from 2000 to 20 through a multiplexing technique.

The result of this simplification is shown in Tables 29 and 30. While this simplification does improve the electronics failure rate by 30 percent, the overall system MTBF of 1640 hours does not meet the system design goal.

6.8 SUMMARY

The results of the reliability analysis indicate that a display system utilizing the DIGISPLAY device is capable of meeting the design goal of 2000 hours MTBF utilizing current fabrication techniques and existing semiconductor technologies. Extension of likely technological developments in the area of large scale integration improves the predicted MTBF of the DIGISPLAY system to 2500 hours.

For the remaining devices the predicted system MTBF fails short of the design goal primarily because of the complexity of modulation and drive circuitry. Also in the case of plasma and ferroelectric the requirements for relatively high switching voltages preclude the application of large scale integration techniques to a significant portion of the display electronics.

The alternate approach utilizing multiplexed modulation and select circuitry for the liquid crystal improves the reliability of this system by a factor of 30 percent, but the final overall MTBF, 1640 hours is still short of the 2000 hour design goal.

TABLE 29 TOTAL SYSTEM FAILURE RATES

MULTIPLEXED LIQUID CRYSTAL

DISPLAY TYPE	DISPLAY & DISPLAY ELTN. F/R (p.p.m.)	OPERATIONAL MODE		
		TV TOTAL F/R (p.p.m.)	FLIR TOTAL F/R (p.p.m.)	RADAR TOTAL F/R (p.p.m.)
LIQUID CRYSTAL	375	400	458	621

TABLE 30 TOTAL SYSTEM MTBF

MULTIPLEXED LIQUID CRYSTAL

DISPLAY TYPE	OPERATIONAL MODE		
	TV MTBF (HOURS)	FLIR MTBF (HOURS)	RADAR MTBF (HOURS)
LIQUID CRYSTAL	2500	2100	1640

7.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the technology review and tradeoff analysis that was performed between twelve advanced non-CRT candidates for the VDS application.

1. In considering the evaluations made and conclusions reached in this report, the reader must keep in mind one basic fact: evaluations are based upon a point system authorized by the Navy to evaluate display devices for a specific application. For other applications orders of preference would undoubtedly be different.

2. The most promising candidates are the five advanced non-CRT display techniques in Groups 1 and 2.

GROUP 1

DIGISPLAY

Liquid Crystal

GROUP 2

Light Emitting Diodes

Ferroelectric

AC Plasma

The Group 1 candidate techniques have approximately a 20 percent performance advantage over the three candidates of Group 2. However, because these display technologies are in a relatively early state of development, a major breakthrough in the research and development effort of any of the five most promising candidates could make it the most attractive candidate.

3. Additional research and development effort is required in each of the advanced non-CRT display technologies of the five most promising candidates in order to bring the performance up to the levels required to fulfill the design goals of a 1980 VDS.

4. The absolute numbers associated with the weighting factor evaluation are not as meaningful as the relative assignment of points (point differential) to the various performance parameters of the twelve display techniques. This consideration is most important in determining the relative ranking and arrangement of the advanced non-CRT display techniques into groups according to their potential of eventually fulfilling the VDS performance goals.

5. Because no one display technique is so far ahead of the other contenders, it is recommended that the most attractive or optimum VDS display technique not be selected at this time. The advances in development among the five most serious contending advanced non-CRT candidate display techniques should be monitored and surveyed for at least one more year before the Navy selects a particular technique for the VDS application.

6. The detailed systems reliability analysis has shown that of the five most promising display techniques, only the DIGISPLAY technique could achieve the design goal of 2000 hours MTBF utilizing current fabrication techniques and existing semiconductor technologies. This is due to the relatively simplified addressing circuitry (low parts count) required by the DIGISPLAY compared with the relatively high complexity of the modulation and driver circuitry (high parts count) of the other techniques.

7. It is recommended that the preliminary system design of the VDS be performed using the DIGISPLAY technique as the example for the baseline design. The DIGISPLAY was rated as one of the two most promising candidates, and it is the technique that Northrop is most familiar with and on which the greatest amount of detailed technical information is available.

8.0 SIMULATION STUDIES

This section describes the static diagnostic tests and the dynamic VDS format simulation evaluations that were conducted during the VDS study. These simulation tests were performed to accomplish two main objectives. The first objective was to obtain experimental information regarding the human engineering requirements for dot matrix displays compared to the conventional CRT raster scanned displays as a guide to the preliminary design of the VDS. The second objective was to verify the flyability of dot matrix formats developed for the takeoff/cruise and landing flight modes with respect to the human factors considerations such as font, size, and spatial groupings of symbols, the placement and contents of the information, movement patterns of pictorial information, and the adaptability of the pilot and systems operator to convert from the existing cockpit displays to the proposed new dot matrix VDS.

8.1 DIAGNOSTIC TESTS

The purpose of these tests was to determine experimentally the optimum scanning standard, resolution, screen brightness, and contrast requirements for a simulated dot matrix display in comparison with a conventional raster scanned CRT display. The measurements and photographs obtained provided human engineering information for the cost-effectiveness trade-off studies to select the optimum design parameters for an operational VDS and insured that the performance specifications for the VDS design are workable.

8.2 DIAGNOSTIC CRT TEST SYSTEM

The CRT test system shown in Figure 47 has the capability to operate either in the conventional TV raster mode or in the simulated dot matrix mode. The image of the slide transparency mounted in the light box or the low resolution CRT monitor of the display format simulation system, is formed by the optical lens system on the vidicon sensor, where it is converted into a video signal by scanning the rear of the vidicon target with a beam in a standard TV scan format (2:1 interlace; vertical field frequency of 60 Hz and vertical frame frequency of 30 Hz). This video signal is then routed to the video amplifier in the camera control unit to be amplified and conditioned such that it can drive the CRT monitor. The sync generator provides the

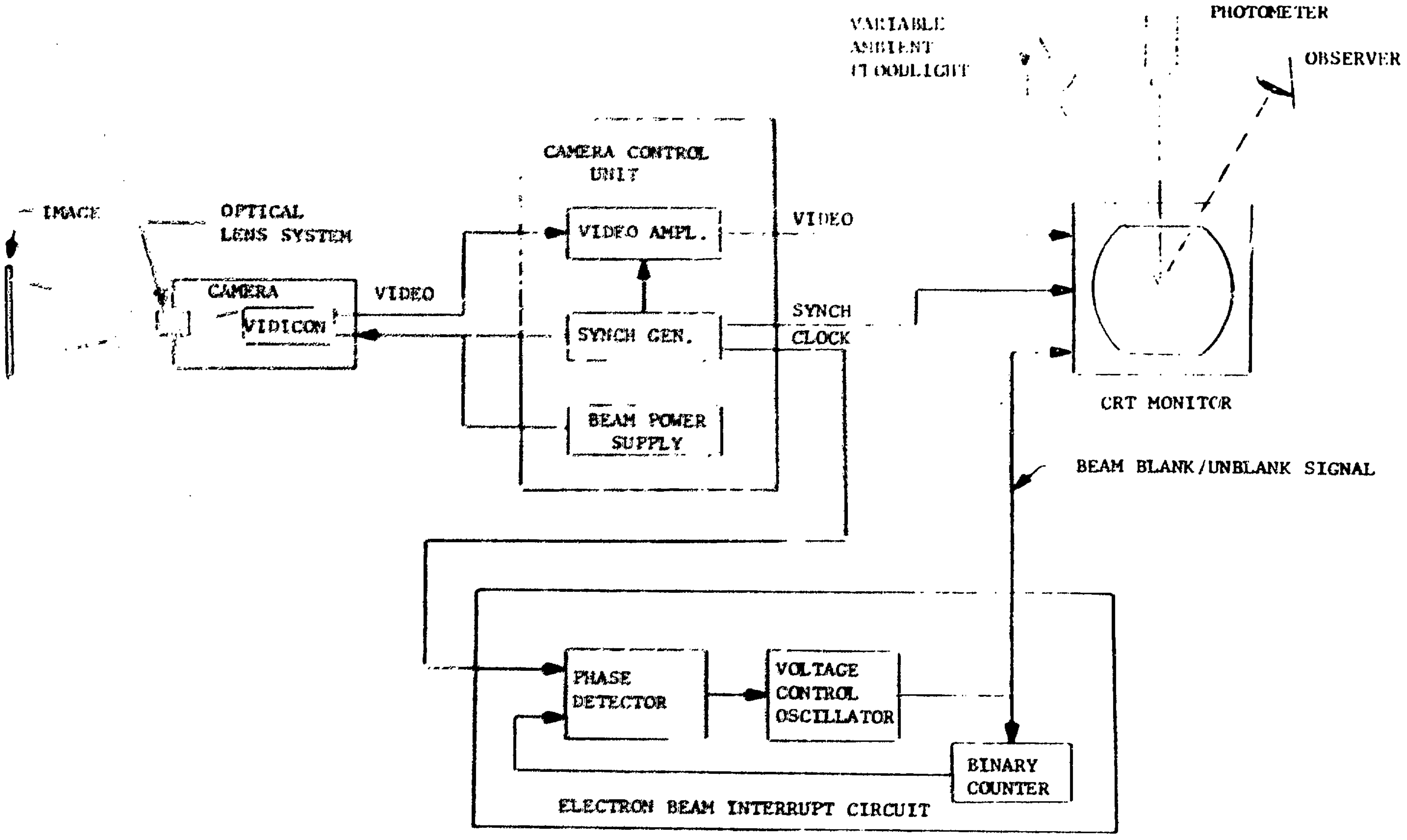


FIGURE 47. SCHEMATIC DIAGRAM - CRT TEST SYSTEM

vidicon camera and the CRT monitor with sync pulses, which dictate the scan rates in both the horizontal and vertical direction.

The electron beam interrupt circuit enables the CRT monitor (which utilizes a conventional TV raster scan technique to paint a picture) to simulate a dot matrix display by blanking and unblanking the video signal in the monitor. This circuit is comprised of a voltage control oscillator, phase detector, and a binary counter. The phase detector compares the frequency of the input clock (from the sync generator) with the frequency of the binary counter, which is driven by the voltage control oscillator. If the frequencies are not in phase a voltage will be generated and applied to the voltage control oscillator to either increase or decrease the frequency of the oscillator (which is the beam blank/unblank signal). In this manner the beam blank/unblank signal will be synchronized with the sync generator, such that the image on the CRT monitor will be modulated with a stable, nonsmearing dot matrix.

This system can be programmed to operate with 875, 945 or 1023 line scanning standards by changing the sync board in the camera control unit, adjusting the horizontal oscillator frequency in the CRT monitor, and adjusting the basic frequency of the voltage control oscillator in the electron beam interrupt circuit. All of the equipment utilized in the CRT test system, the vidicon camera, the camera control unit, and the CRT monitor, has at a minimum, a video bandwidth of 20 MHz which is adequate for scanning rates up to 1023 lines/frame.

8.3 STATIC SIMULATION TEST PROCEDURE

The static simulation test procedure utilized the light box and the CRT test system to obtain test data, using tri-bar resolution patterns and EIA Standard gray scale test transparencies. The objective was to determine the greatest number of line-pairs and gray shades that can be resolved or detected on the display, as a function of the following variable parameters:

- Type of display techniques used
  1) Conventional TV raster scan
  2) Dot matrix

3. The horizontal oscillator frequency control on the CRT monitor was adjusted to stabilize the image on the CRT monitor.

4. With a wideband oscilloscope tied to the video output of the camera control unit, the cable delay control on the deflection unit was adjusted until the greatest (in amplitude) video signal was obtained. The video signal was 1 volt peak-to-peak riding on top of a 1 volt sync pulse.

8.4 TEST PROCEDURE

This test procedure was run three times, once for each different scanning standard (875, 945 and 1023) which determined the number of resolution lines or elements utilized by the display.

1. Using the resolution test transparency, the vertical and the horizontal size control on the CRT monitor was adjusted such that the 6.5625 inch square test transparency was 9.46 inch square on the CRT monitor with the vertical raster size of 9.5 inches.

   NOTE: The CRT monitor adjusted in this manner provided a display with 1) 85 lines/inch resolution density with a 9.46 inch square screen size in the 875 scanning rate system; 2) 92 lines/inch resolution density with a 9.46 inch square screen size in the 945 scanning rate system; or 3) 100 lines/inch resolution density with a 9.46 inch square screen size in the 1023 scanning rate system.

2. The brightness level of the image and the background were measured with a photometer, at the test transparency and also at the CRT monitor.

   NOTE: The brightness levels recorded for positions 1 and 2 were used as a reference, so that the brightness and contrast control on the CRT monitor and the variable light source of the light box could be readjusted to these values, if required, after the system had been reconfigured to another scanning rate.

3. The signal and the noise component of the video signal at the output of the camera control unit at each one of the 12 positions described above was measured, using a wideband oscilloscope, recorded and photographed.

4. The highest number of line-pairs that the observer could resolve with no ambient illumination at a distance of 28 and 14 inches from the CRT monitor were recorded.

5. Steps 2, 3 and 4 (except the taking of photographs) for two other image brightness levels by readjusting the variable light source of the light box were repeated.

6. The variable light source of the light box was readjusted to provide 700 foot-Lamberts on the translucent diffusing screen (without the test transparency) and the gray scale test transparency was inserted.

7. The brightness level of each one of the 16 shades of gray was measured with a photometer at the test transparency and also at the CRT monitor.

8. The video signal and the noise component of the video, at the output of the camera control unit, was measured and photographed to show the amplitude of the video at each of the 16 gray shade positions.

9. The gray scale image that could be detected by an observer located 28 inches away from the CRT monitor was photographed.

10. The ambient light intensity directed on the CRT monitor was measured with a photometer and the detectable gray shades viewed (by an observer) for each one of the three different ambient light conditions were recorded.

11. The two selected display format transparencies were inserted (one at a time) into the light box, and photographs were taken of the image on the CRT monitor. These photographs (total of six, two for each different scanning rate) were used to show the difference in the display, caused by changing the number of resolution lines with a fixed screen size.

    NOTE: Two display formats, landing mode and the weapon delivery air-to-ground mode, were selected because they represent the two different types of pictorial background (simulated view and the real image) used in the VDS.

12. One of the display formats was used to adjust the vertical and horizontal size control on the CRT monitor, such that the 6.5625 inch square image of the transparency was displayed on the CRT monitor with 100 lines/inch resolution.

NOTE: The image size on the CRT monitor was 1) 8.07 inch square in an 875-line scanning rate system, 2) 8.74 inch square in a 945-line scanning system, or 3) 9.46 inch square in a 1023-line scanning system.

13. All of the different display format transparencies were inserted (one at a time) into the light box, and photographs of the image on the CRT monitor were obtained. These photographs taken in this step were used to show the difference in the display, caused by changing the screen size with a fixed number of scanning lines.

Steps 1 through 13 were repeated with the beam interrupt circuit activated to obtain data and photographs related to the dot matrix type of presentation.

NOTE: The frequency of the beam blank/unblank signal in the CRT monitor was 1) 26 MHz for the 875-line scanning rate system, 2) 31 MHz for the 945-line scanning rate system, and 3) 37 MHz for the 1023-line scanning rate system.

The data obtained from the resolution and gray scale simulation measurements are listed in Tables 31 and 32, respectively. In Table 31 the first value listed for each observer refers to performance at a 14-inch viewing distance and the second value at a 28-inch viewing distance.

TABLE 31 RESOLUTION MEASUREMENT DATA

TEST NO.	TYPE OF DISPLAY	NO. OF LINES	RES. IN LPI	*	DETECTABLE LINE-PAIRS HORIZONTAL	VERTICAL	OBSERVER
1	Raster	640	80	8	265	265	McDade
					236	265	
					297	265	Noda
					236	210	
					186	210	Meyer
					186	210	
					333	265	Rusk
					297	236	
					265	236	Yoern
					265	236	
					372	297	Di Benedetto
					297	265	
2	Dot	640	80	8	265	265	McDade
					236	265	
					265	210	Noda
					236	210	
					186	166	Meyer
					186	166	
					297	186	Rusk
					265	210	
					265	210	Yoern
					265	236	
					265	186	DiBenedetto
					236	186	
3	Raster	720	80	9	333	333	McDade
					297	333	
					333	297	Noda
					297	265	
					210	236	Meyer
					210	210	
					372	333	Rusk
					333	236	
					297	265	Yoern
					297	265	
					333	236	DiBenedetto
					297	210	
4	Dot	720	80	9	333	333	McDade
					297	297	
					333	265	Noda
					265	236	
					210	186	Meyer
					186	186	
					333	236	Rusk
					265	236	
					265	210	Yoern
					265	210	
					265	265	DiBenedetto
					265	186	

*SCREEN SIZE (INCHES)

TABLE 31 RESOLUTION MEASUREMENT DATA (Continued)

TEST NO.	TYPE OF DISPLAY	NO. OF LINES	RES. IN LPI	*	DETECTABLE LINE-PAIRS HORIZONTAL	DETECTABLE LINE-PAIRS VERTICAL	OBSERVER
5	Raster	800	80	10	372	372	McDade
					333	333	
					372	333	Noda
					333	297	
					236	265	Meyer
					236	236	
					420	297	Rusk
					333	265	
					372	333	Yoern
					333	297	
					372	333	DiBenedetto
					372	265	
6	Dot	800	80	10	372	372	McDade
					333	333	
					333	297	Noda
					297	265	
					297	236	Meyer
					236	210	
					372	297	Rusk
					297	265	
					297	265	Yoern
					297	265	
					297	372	DiBenedetto
					297	372	
7	Raster	880	80	11	372	372	McDade
					333	372	
					372	333	Noda
					372	333	
					297	265	Meyer
					265	236	
					420	297	Rusk
					333	297	
					372	265	Yoern
					372	265	
					372	333	DiBenedetto
					372	333	
8	Dot	880	80	11	372	372	McDade
					333	333	
					333	333	Noda
					333	333	
					265	210	Meyer
					26[illegible]	210	
					372	297	Rusk
					297	265	
					372	265	Yoern
					333	297	
					297	265	DiBenedetto
					265	236	

*SCREEN SIZE (INCHES)

TABLE 31 RESOLUTION MEASUREMENT DATA (Cont'd)

TEST NO.	TYPE OF DISPLAY	NO. OF LINES	RES. IN LPI	*	DETECTABLE LINE-PAIRS HORIZONTAL	VERTICAL	OBSERVER
9	Raster	800	100	8	297	297	McDade
					236	236	
					265	210	Noda
					236	210	
					236	186	Meyer
					210	166	
					372	236	Rusk
					265	186	
					333	210	Yoern
					297	210	
					236	186	Di Benedetto
					236	166	
10	Dot	800	100	8	265	265	McDade
					236	236	
					265	210	Noda
					236	186	
					210	148	Meyer
					210	148	
					297	186	Rusk
					236	166	
					265	210	Yoern
					265	210	
					265	166	Di Benedetto
					265	148	
11	Raster	900	100	9	297	297	McDade
					265	265	
					333	265	Noda
					265	236	
					265	210	Meyer
					236	186	
					420	265	Rusk
					297	236	
					333	236	Yoern
					333	236	
					297	210	DiBenedetto
					297	186	
12	Dot	900	100	9	297	297	McDade
					265	265	
					297	236	Noda
					265	210	
					265	166	Meyer
					210	166	
					333	210	Rusk
					265	210	
					372	236	Yoern
					333	236	
					297	186	DiBenedetto
					236	186	

*SCREEN SIZE (INCHES)

TABLE 31 RESOLUTION MEASUREMENT DATA (Cont'd)

TEST NO.	TYPE OF DISPLAY	NO. OF LINES	RES. IN LPI	*	DETECTABLE LINE-PAIRS HORIZONTAL	VERTICAL	OBSERVER
13	Raster	1000	100	10	372	372	McDade
					333	333	
					372	297	Noda
					333	265	
					297	236	Meyer
					265	210	
					472	333	Rusk
					372	265	
					372	297	Yoern
					372	297	
					372	297	DiBenedetto
					333	297	
14	Dot	1000	100	10	372	372	McDade
					297	333	
					372	297	Noda
					333	265	
					297	210	Meyer
					265	186	
					420	265	Rusk
					333	265	
					372	297	Yoern
					372	297	
					372	210	Di Benedetto
					297	210	
15	Raster	1100	100	11	472	472	McDade
					420	420	
					372	333	Noda
					372	297	
					420	265	Meyer
					297	236	
					472	297	Rusk
					372	297	
					420	372	Yoern
					372	372	
					372	265	DiBenedetto
					333	236	
16	Dot	1100	100	11	472	472	McDade
					420	420	
					372	333	Noda
					372	297	
					297	210	Meyer
					265	210	
					472	265	Rusk
					333	265	
					420	333	Yoern
					372	333	
					372	236	DiBenedetto
					265	210	

*SCREEN SIZE (INCHES)

TABLE 31 RESOLUTION MEASUREMENT DATA (Cont'd)

TEST NO.	TYPE OF DISPLAY	NO. OF LINES	RES. IN LPI	*	DETECTABLE LINE-PAIRS HORIZONTAL	DETECTABLE LINE-PAIRS VERTICAL	OBSERVER
17	PHOTOGRAPH ONLY NO VIDICON OR DISPLAY SYSTEM			TRI-BAR CHART 6.5"	3/5 666	3/5 666	McDade
					3/3 530	3/3 530	
					4/2 945	3/6 744	Noda
					3/2 472	3/4 420	
					4/5 1331	4/3 1057	Meyer
					3/2 472	3/1 420	
					4/4 1187	4/3 1057	Rusk
					3/2 472	3/2 472	
					4/2 945	4/2 945	Yoern
					3/6 744	3/5 666	
					4/4 1187	4/3 1057	Di Benedetto
					3/3 530	3/3 530	
	Raster	800	80	10"	265	236	Neil Douglas
					265	236	
	Dot	800	80	10"	265	236	
					236	236	
	Photograph			6.5"	4/1 844	4/1 844	
					3/4 593	3/3 530	
	Raster	720	80	9"	297	236	
					236	210	
	Dot	720	80	9"	236	210	
					210	210	
	Raster	640	80	8"	210	186	
					210	186	
	Dot	640	80	8"	236	186	
					210	186	
	Raster	880	80	11"	333	297	
					297	265	
	Dot	880	80	11"	333	297	
					297	265	
	Raster	800	100	8"	265	186	
					236	186	
	Dot	800	100	8"	210	186	
					186	148	
	Raster	900	100	9"	210	186	
					210	106	
	Dot	900	100	9"	210	186	
					210	186	
	Raster	1000	100	10"	372	265	
					333	265	
	Dot	1000	100	10"	333	265	
					333	265	
	Raster	1100	100	11"	333	265	
					333	265	
	Dot	1100	100	11"	333	265	
					333	265	

TABLE 32 DATA SHEET

GRAY SCALE TEST TRANSPARENCY

Mode of Operation:

875 Lines ☒ 945 lines ☐ 1023 lines ☐

Conventional T.V. Raster ☒ Dot Matrix ☐

Noise Level (Step 9) 0.1 volts P-P

	GRAY SCALE POSITIONS															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Step 8 Reference measured at the test transparency in ft-Lamberts	600	460	360	280	215	170	140	118	105	87	80	76	73	74	75	90
Step 9 Video measured at the output of the camera control unit in volts	.9	.75	.6	.5	.4	.3	.25	.2								
Step 10 4 ft-Lambert Ambient	x	x	x	x	x	x	x	x	x	x	x	x				
Detectable gray scales by the observer	36	27	20	15	11	9	8	7.5	7	7	6.5	6.5				
Step 11	x	x	x	x	x	x	x	x	x	x						
Detectable gray scales by the observer with 20 ft-Lamberts ambient light	48			31				24		21						
Step 11	x	x	x	x	x	x	x	x								
Detectable gray scales by the observer with 34 ft-Lamberts ambient light	60			43				35								
Step 11	x	x	x	x	x	x	x									
Detectable gray scales by the observer with 55 ft-Lamberts ambient light	80			64		58	57									

Photo 4

Remarks: ____________________

Test Engineer T. Noda Observers ____________ Date 4/27

TABLE 32 DATA SHEET

GRAY SCALE TEST TRANSPARENCY (Cont'd)

Mode of Operation:

875 Lines ☒ 945 [illegible] [illegible] Lines ☐

Conventional T.V. Raster ☐ Dot Matrix ☒

Noise Level (Step 9) 0.1 volts P-P

	GRAY SCALE POSITIONS															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Step 8 Reference measured at the test transparency in ft-Lamberts																
Step 9 Video measured at the output of the camera control unit in volts																
Step 10 4 ft-Lambert Ambient	•	•	•	•	•	•	•	•	•	•	•	•				
Detectable gray scales by the observer	38	30	23	17	13	11.5	9.5	8	8	8	[illegible]	[illegible]				
Detectable gray scales by the observer with 20 ft-Lamberts ambient light	30			33				16		21						
Step 11	•	•	•	•	•	•	•	•								
Detectable gray scales by the observer with 34 ft-Lamberts ambient light				44				38								
[illegible]	•	•	•	•	•	•	•									
Detectable gray scales by the [illegible] with 56 ft-Lamberts ambient light				43		19	34									

[illegible]: ______

Test Engineer T. Rude Observers ______ Date ______

TABLE 32 DATA SHEET

GRAY SCALE TEST TRANSPARENCY (Cont'd)

of Operation

875 Lines ☐ 945 line ☐ ☐

Conventional T.V. Raster ☐ Dot Matrix ☐

Noise Level (step 9) 0.1 volts P-P

	GRAY SCALE POSITIONS															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Step [illegible] Reference measured at the test transparency in ft-Lamberts																
Step 9 [illegible] measured at the output of the camera control unit in volts	.9	.75	.62	.5	.4	.3	[illegible]	.25								
Step 10 [illegible] ft-Lambert Selectable gray scales by the observer	37	29	22.5	17	[illegible]	[illegible]	[illegible]	9	8	[illegible]	[illegible]	[illegible]	[illegible]			
Step 11 Selectable gray scales by the observer with 10 ft-Lamberts ambient light	47			18				[illegible]		[illegible]	[illegible]					
Step [illegible] Selectable gray scales by the observer with 35 ft-Lamberts ambient light	62			42				[illegible]								
[illegible] Selectable gray scales by the observer with 35 ft-Lamberts ambient light	62			43				[illegible]								

Test Engineer [illegible] Observers Date

Best Available Copy

TABLE 32

DATA SHEET

GRAY SCALE TEST TRANSPARENCY (Cont'd)

Mode of Operation:

875 Lines ☐ 945 lines ☒ 1023 lines ☐

Conventional T.V. Raster ☐ Dot Matrix ☒

Noise Level (Step 9) 0.1 volts P-P

	GRAY SCALE POSITIONS																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Step 8 Reference measured at the test transparency in ft-Lamberts																	
Step 9 Video measured at the output of the camera control unit in volts																	
Step 10 5 ft-Lambert	x	x	x	x	x	x	x	x	x	x	x	x	?				
Detectable gray scales by the observer	37	30	24	20	16.5	14	12.5	10	9	8.5	7	7.5	7.5				Neg. 8
Step 11	x	x	x	x	x	x	x	x	x	x	x						
Detectable gray scales by the observer with 18 ft-Lamberts ambient light	46			27				22		20	19						
Step 11	x	x	x	x	x	x	x	x	x								
Detectable gray scales by the observer with 35 ft-Lamberts ambient light	57			40				36	35								
Step 11	x	x	x	x	x	x	x	x									
Detectable gray scales by the observer with 55 ft-Lamberts ambient light	80			65				57									

Remarks: ____________________

Test Engineer T. Noda Observers ____________ Date 5/1

DATA SHEET

TABLE 32 GRAY SCALE TEST TRANSPARENCY (Cont'd)

Mode of Operation:

875 Lines ☐ 945 lines ☐ 1023 lines ☒

Conventional T.V. Raster ☒ Dot Matrix ☐

Noise Level (Step 9) 0.1 volts P-P

	GRAY SCALE POSITIONS																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Step 8 Reference measured at the test transparency in ft-Lamberts																	
Step 9 Video measured at the output of the camera control unit in volts	0.9	.75	.65	.56	.5	.42	.35										Photo 20
Step 10 5 ft-Lambert Detectable gray scales by the observer	x	x	x	x	x	x	x	x	x	x	x	x					
	37	29.5	23.5	18	14.5	11	9.5	8.5	8	7.5	7.5	7	7				Neg. 12
Step 11 Detectable gray scales by the observer with 20 ft-Lamberts ambient light	x	x	x	x	x	x	x	x	x	x	x						
	52			35				26		22	21						
Step 12 Detectable gray scales by the observer with 33 ft-Lamberts ambient light	x	x	x	x	x	x	x	x	x								
	60			44				35	34								
Step 13 Detectable gray scales by the observer with 95 ft-Lamberts ambient light	x	x	x	x	x	x	x	x									
	81			64				57									

Remarks: ______

Test Engineer T. Noda Observers ______ Date 5/3

TABLE 32

DATA SHEET

GRAY SCALE TEST TRANSPARENCY (Cont'd)

Mode of Operation:

875 Lines ☐ 945 lines ☐ 1023 lines ☒

Conventional T.V. Raster ☐ Dot Matrix ☒

Noise Level (Step 9) 0.1 volts P-P

	GRAY SCALE POSITIONS															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Step 8 Reference measured at the test transparency in ft-Lamberts																
Step 9 Video measured at the output of the camera control unit in volts																
Step 10 5 ft-Lambert	x	x	x	x	x	x	x	x	x	x	x	x				
Detectable gray scales by the observer	36	29	24.5	19.5	16	12.5	10.5	9.5	9	8.5	8	8	7.5			
Step 11	x	x	x	x	x	x	x	x	x	x	x					
Detectable gray scales by the observer with 20 ft-Lamberts ambient light	51				34			25		22	21					
Step 11	x	x	x	x	x	x	x	x	x							
Detectable gray scales by the observer with 33 ft-Lamberts ambient light	57				42			35	34							
Step 11	x	x	x	x	x	x	x	x								
Detectable gray scales by the observer with 55 ft-Lamberts ambient light	78				62			57								

Neg. 14

Remarks:

Test Engineer T. Noda Observers Date 5/3

8.5 DIAGNOSTIC SIMULATION TEST CONCLUSIONS

As may be seen from Table 31 , there is quite a disparity in visual performance among a randomly selected group of observers. Although all observers used for these tests had either normal or corrected 20:20 vision, the subjective nature of the decision process, i.e., whether a group of equi-spaced bars were resolvable or not, resulted in the presence of some bias in the recorded data. In general, those observers who had some familiarity with tests of this type tended to score high while those with little a priori knowledge scored low. The trends, however, remained consistent from one observer to the next, and this in itself justified a belief in the validity of the study.

To separate out the general trends buried in the raw data, the sample mean and the unbiased sample variance were computed for each set of data in accordance with the following standard formulas

$$\bar{x} = \frac{1}{n}\left(x_1 + x_2 + x_3 \cdot \cdot \cdot \cdot \cdot + x_n\right)$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} \left(x_i - x_n\right)^2$$

where n is the sample size. The mean values so calculated are plotted in Figures 48 and 49 as a function of the display width. The first figure illustrates the situation at the standard cockpit viewing distance of 28 inches and the second at a close-up distance of only 14 inches. Note that the trends as indicated by both situations are nearly identical. The main difference being that the detectable resolution at 14 inches is somewhat higher than that at 28 inches, an intuitively satisfying result. Note also that the trends as indicated by the two scanning modes, raster and dot matrix, are likewise nearly identical. The standard deviation in all cases was found to be approximately ±45 line pairs per picture width. (Dot matrix performance is represented by the dashed curves.)

To obtain an estimate of how well the sample means indicated in Figures 48 and 49 reflect the actual mean of an infinite sample population, it was assumed that the data was normally distributed and that Student's t test was applicable. This test determines the confidence interval around the sample mean within which the actual mean lies. Mathematically we have that the actual

MEAN VALUES OF RESOLUTION PERFORMANCE

28" VIEWING DISTANCE

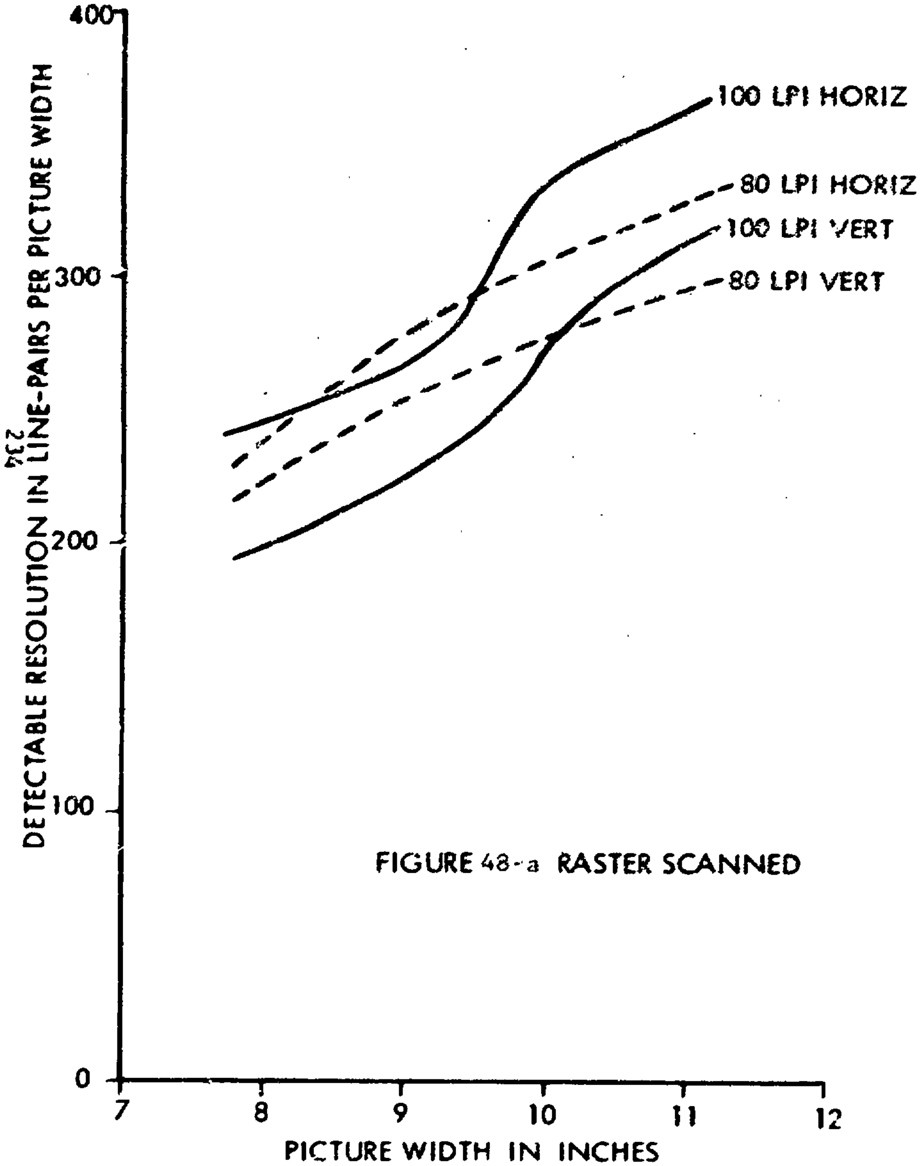


FIGURE 48-a RASTER SCANNED

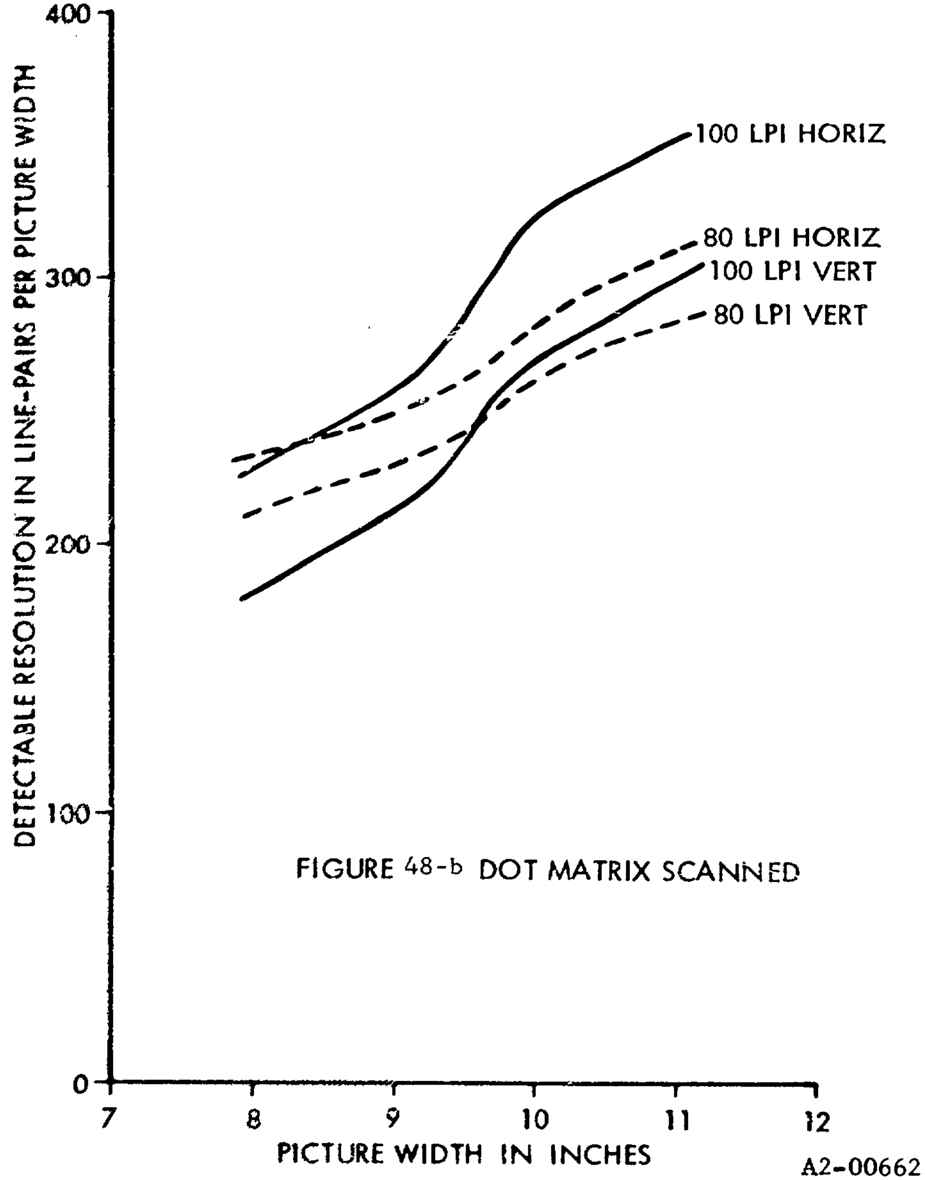


FIGURE 48-b DOT MATRIX SCANNED

A2-00662

MEAN VALUES OF RESOLUTION PERFORMANCE
14" VIEWING DISTANCE

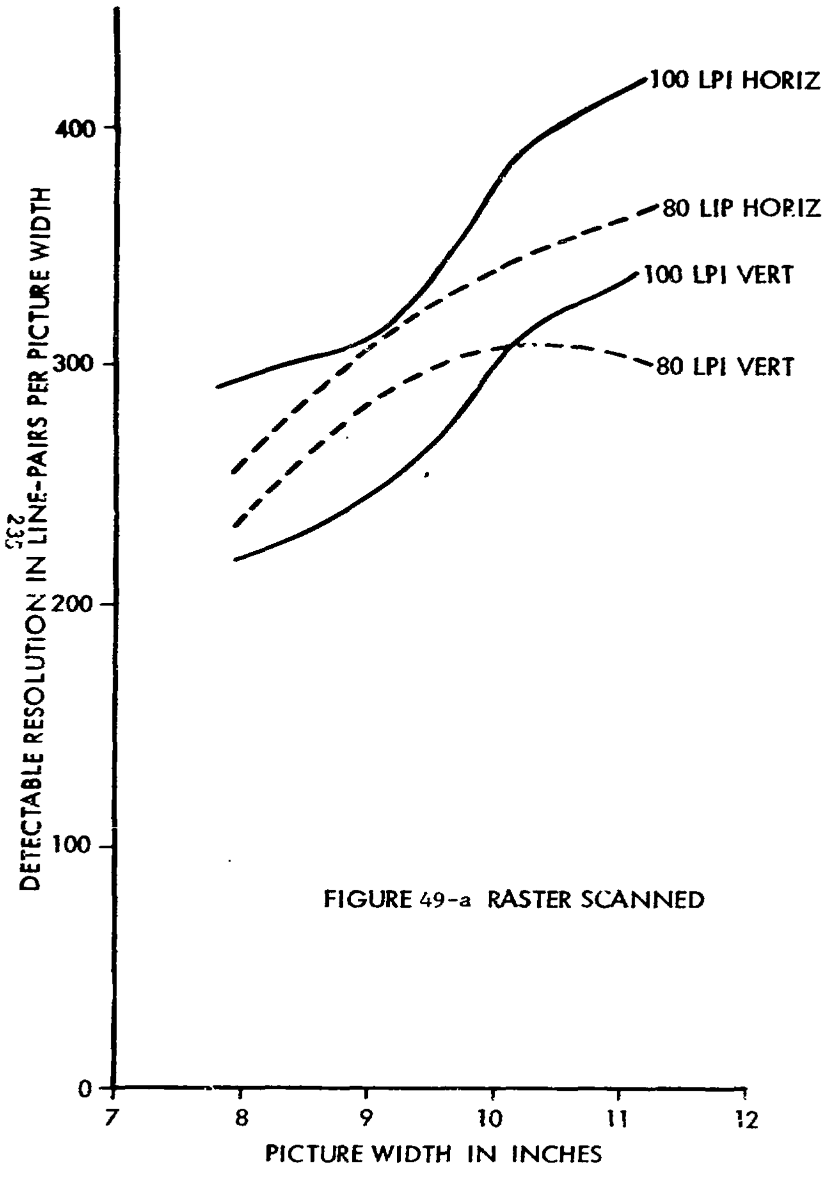


FIGURE 49-a RASTER SCANNED

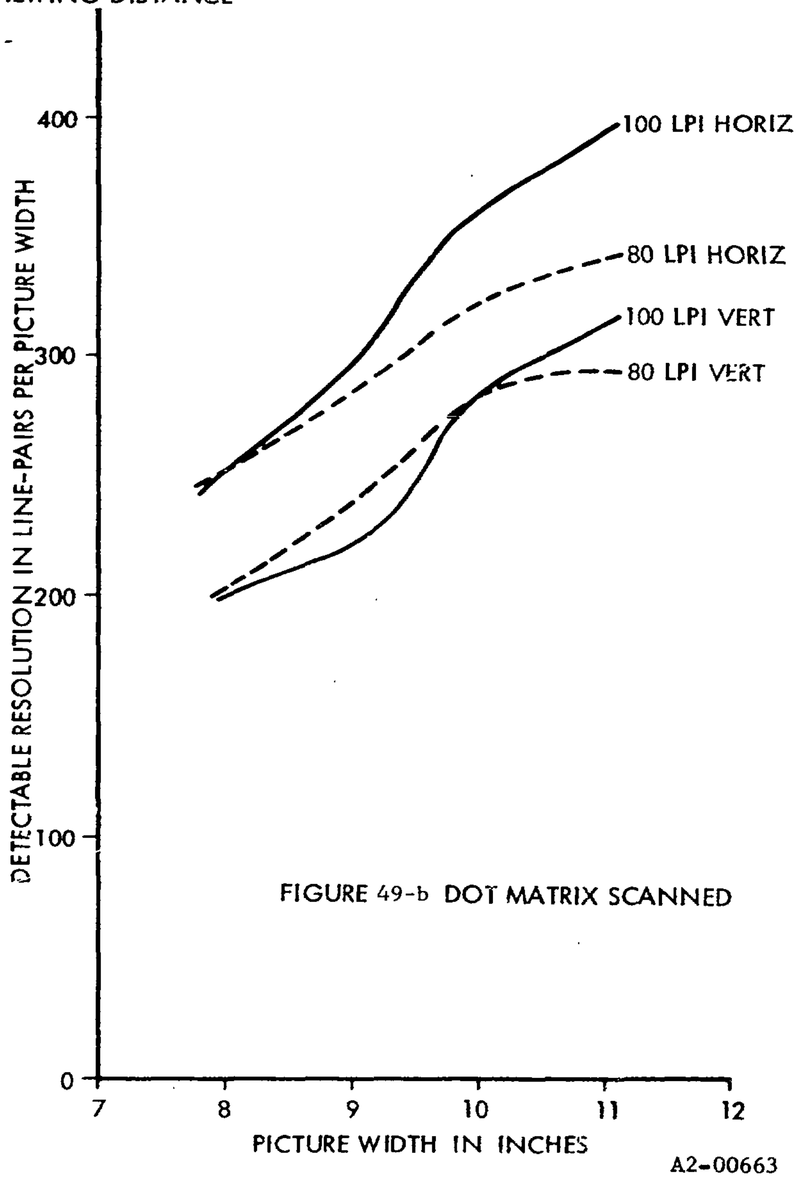


FIGURE 49-b DOT MATRIX SCANNED

A2-00663

mean is located within the interval defined by

$$\bar{x} \pm \frac{t_{\alpha;\, n}}{\sqrt{n}} s$$

where $t_{\alpha;n}$ is the α confidence point of the t-distribution for n degrees of freedom (independent samples). For 90 percent confidence limits with n = 8 and s = 45, the actual mean is located within the interval defined by

$$\bar{x} \pm \frac{1.860}{\sqrt{8}} (45)$$

i.e., ±30 line pairs around the sample mean.

A few rather disconcerting questions are raised by Figures 48 and 49 . For example, it is not known why the 100 l.p.i. (line pairs per inch) curves are s-shaped, whereas the 80 l.p.i. curves are not. Although the rather wide confidence interval could account for this behavior in any one curve, it cannot account for the consistency displayed by each and every curve. Hence, the phenomenon responsible for this s-shape must be real and not just a quirk of the data. An even bigger question is raised by the indication of poorer visual performance at 100 l.p.i. than at 80 l.p.i. when the display size is less than 10 inches in width. This indication is especially apparent for the detection of vertically-oriented bars. One would intuitively expect the performance at 100 l.p.i. to be always better than that at 80 l.p.i., but this is apparently not true. It would have been instructive to have conducted further tests designed to arrive at an explanation for these strange results, but no time was available under the constraints of this contract.

The one general conclusion which may be drawn from these figures is that there is a distinct improvement in visual performance with either the raster or the dot matrix scan format as the screen size is increased. This performance seems to increase rapidly through the range of 8 to 10 inches with a slight tendency toward leveling off with even larger display sizes. Another conclusion which may be reached is that the raster scan exhibits only slightly better performance than does the dot matrix presentation. This is evident in Figure 50 where the dot matrix performance is plotted as a percentage of the raster scan performance. In view of the rather large standard deviation involved, however, this last conclusion is not statistically significant.

COMPARISON OF DOT MATRIX TO RASTER SCAN PERFORMANCE

FIGURE 50-a , 5" VIEWING DISTANCE

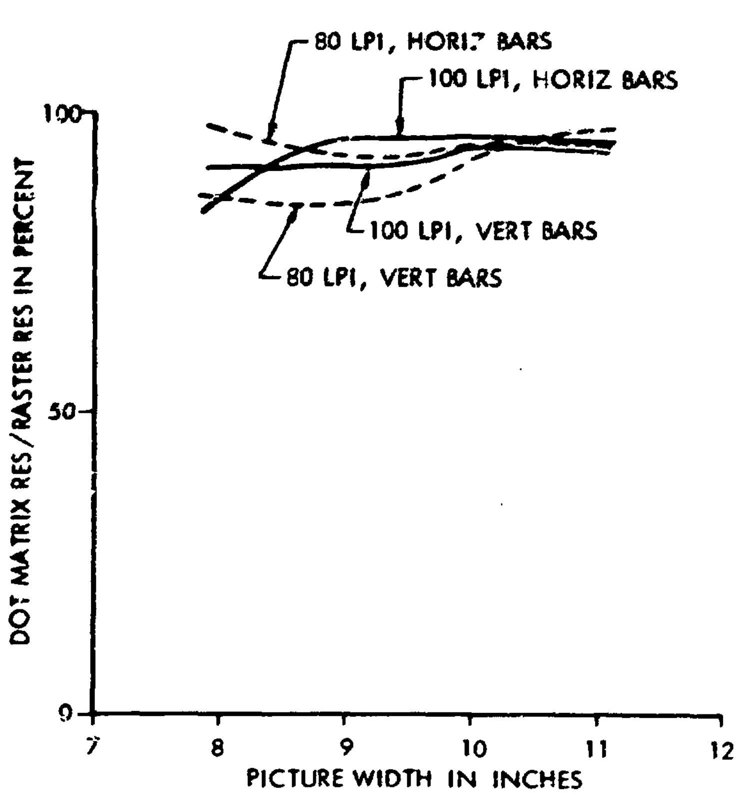
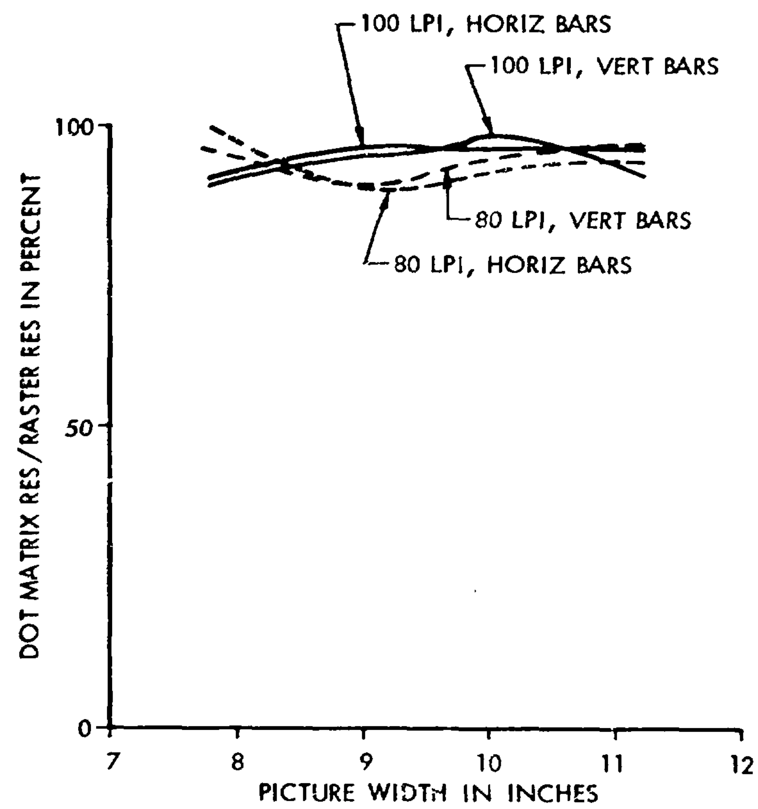


FIGURE 50-b 28" VIEWING DISTANCE



A2-00664

The gray scale test data indicated that there is no significant difference between the raster scan and simulated dot matrix gray scale recognition capability for 875, 945, or 1023 TV line scanning standards. When most test observers optimized the brightness and contrast settings on the monitor for maximum resolution performance, there was a loss of two shades of gray scale recognition due to the lower beam intensity which reduced dynamic range.

8.6 DYNAMIC SIMULATION TESTING

In the dynamic simulation phase of this program, two of the display formats were presented on a CRT monitor. The formats were varied to present a short mission simulation. This presentation was viewed by a series of qualified observers, who then completed a questionnaire. The questionnaire was prepared to allow evaluation of the organization of the formats, the presentation of data within the formats, the symbol quality, and the picture quality for both 875 line raster and 810X810 dot matrix presentations.

8.6.1 Dynamic Simulation Equipment

Figure 51 is a block diagram of the equipment used in the dynamic simulation study. The simulation "flight data" was read on the paper-tape reader and sent to the general purpose computer. The computer processes this data and issues instructions to the display generator. The display generator forms the required images and stores them on the disc memory. The image information is retrieved from the disc and used to refresh a 525 line television monitor. The picture on this monitor is photographed by a high resolution vidicon camera and redisplayed on a 875 line monitor. This high resolution monitor has a beam-interrupt circuit which enables the image to be shown in a simulated dot-matrix format.

The teletypewriter is a modified ASR 33 with paper-tape punch and independent paper-tape reader. Information transfer to and from the computer is full duplex, at 10 characters per second.

The computer is a Hewlett-Packard model 2100A with 4000 words of memory. This computer features a 16 bit word length, hardware multiply and divide, and multi-level priority interrupts. The computer receives aircraft maneuvering instructions from the paper-tape reader. These instructions are analyzed and the new aircraft situation is calculated. The aircraft situation is translated into a series of instructions which are sent to the display generator. The computer then waits until the display generator has processed all instructions. At this time, new flight data is received from the paper-tape reader, and the cycle is repeated.

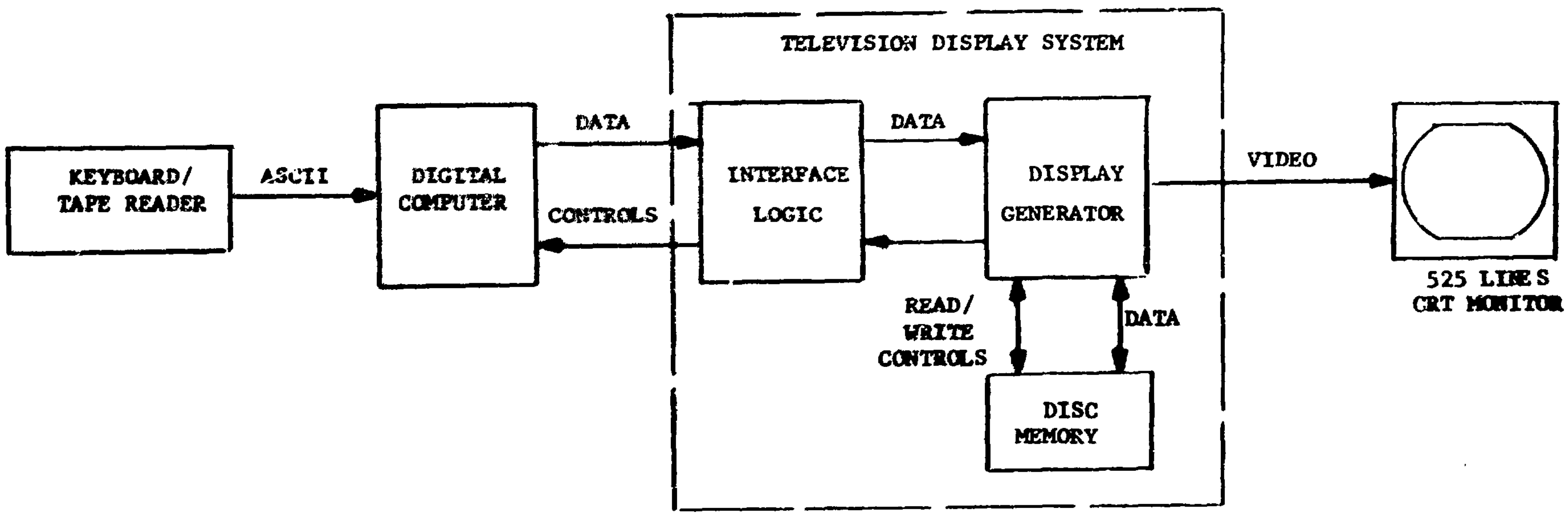


FIGURE 51 BLOCK DIAGRAM - DISPLAY FORMAT SIMULATION SYSTEM

The disc memory is a Data Disc Model 5250. This memory is of a head-per-track design with an 1800 revolution per minute speed. Sixteen tracks are used on the disc to store the information content of four black and white video images. These images can be combined into two pictures with four shades of gray or one picture with sixteen shades of gray.

Due to the serial nature of the disc memory and the complexity of the required images, six revolutions of the disc (one-fifth of a second) are required to change the display image. To avoid objectional smearing and jumping of the images, a combinational technique using all four disc channels was employed. Disc channels A and B stored image information that does not change during the flight simulation. Channels C and D contain information which must be regenerated to reflect changes in the aircraft situation. Initially, channels A, B and C are logically combined to form a four shade video image. Simultaneously, the information on channel D is being rewritten. When channel D is completely regenerated, a multiplexer is switched and channels A, B, and D are now combined to form the display image. Channel C can now be regenerated to reflect changes in aircraft situation without disturbing the displayed image. The reader will note that each channel consists of four tracks on the disc and is essentially a complete black and white image. Also note that the multiplexing and combining is done with the data in digital form as it comes from the disc. The combined data then passes through a D/A converter and video amplifier.

The display generator is a Data Disc Model 6601. This device converts instructions from the computer into picture elements and stores the image information on the disc memory. The display generator also contains the D/A converters, video amplifiers, and sync generation circuitry. The Data Disc display generator has five basic modes of operation which are software selectable. These modes are summarized below:

Alphanumeric Mode: In this mode, a block of one or more alphanumeric characters is generated, starting at a preset X and Y address. The characters can be chosen from a 128 character set including upper and lower case alphabet, numerics, punctuation and special-purpose mathematical symbols. The characters can be generated in four fonts and can be displayed light on dark or dark on light background. This mode is heavily used in the heading, altitude, airspeed, mach number, and pitch scales of the VDS formats.

Graphic Line Mode: In the graphic line mode, a rectangular area is written, given the four corner addresses. The area may be written either dark or light. This mode is used in the simulation to form the horizon and the pitch ladder. Since only rectangular areas are automatically written, angular lines are approximated using rectangles or line segments. The calculation of the addresses required to approximate an angular line is done in the computer.

Graphic Data Mode: In the graphic data mode, twelve 8-bit bytes of data from the computer are put on the display in the form of an 8X12 matrix. The purpose of this mode is to allow the use of special characters not included in the Data Disc generator character set. This mode is used to form the roll index pointer in the simulation.

Display Data Mode: In the display data mode, bytes of data from the computer are written directly on the display. This mode is not used in the simulation.

Graphic Chart Mode: The graphic chart mode is similar to the display data mode except that one line, or partial line, of data is repeated on a variable number of adjacent lines. This mode is not used in the simulation.

All display generation steps require several instructions from the computer. These instructions may be divided into the following categories:

Control Instructions: The control instructions include such functions as erase, reset, and channel select.

Mode Instructions: The mode instructions determine which of the above modes the display generator will operate in. The instruction also includes bits to set size, and color (gray shade) options.

Address Instructions: The address instructions set the X and Y positions at which writing will start in any of the modes. In the graphic line and graphic chart modes, address instructions are also required to set the final position of the writing.

Data Instructions: Data instructions contain the data to be placed on the display. In the alphanumeric mode, the data consists of eight bit character codes. In the graphic line mode, data consists of new addresses. In all other modes, the data is the actual pattern desired on the display. Data may be sent in blocks of one or more words.

The reader will please note that the above paragraphs do not constitute a complete description of the Data Disc Display Generator. Within each mode there are numerous options of size, shade, and methods of writing. These options give the system a great amount of versatility.

The 525 line monitor used was a modified 1024 line, 14 inch diagonal CONRAC monitor. This device was chosen because of its high bandwidth and excellent linearity. The 875 line camera and monitor were the same devices used in the static testing phase. The beam-interrupt circuit was used to simulate an 810X810 dot matrix display. While the equipment used was all of high quality, the image on the 875 line monitor was not as crisp as the 525 line picture. This was due to the predictable MTF loses in the camera and high resolution monitor.

8.6.2 Simulation Procedure

The dynamic simulation procedure was to have an eight minute "flight" viewed on the 875 line display. The flight was viewed at least once with a standard raster display and at least once with a simulated dot matrix presentation. The viewers then completed a questionnaire on the general acceptability of the display presentation. A verbal interview ranging from one-half to three hours was held to get further information and to expand on any weaknesses noted on the questionnaire.

This procedure was repeated for groups of one to three observers for a total of eight observers. Six of the eight were former military pilots and all are presently involved in the design or evaluation of military avionics equipment.

Figures 52 and 53 are the recommended formats for the take-off/cruise and landing modes of flight. To investigate some of the features of these formats, and to simplify the software required to generate the display, some exceptions were made to the formats as shown. The basic features and the exceptions incorporated in the simulation are outlined in Table 33.

VDS FORMAT TAKE-OFF/CRUISE MODE

FIGURE 52

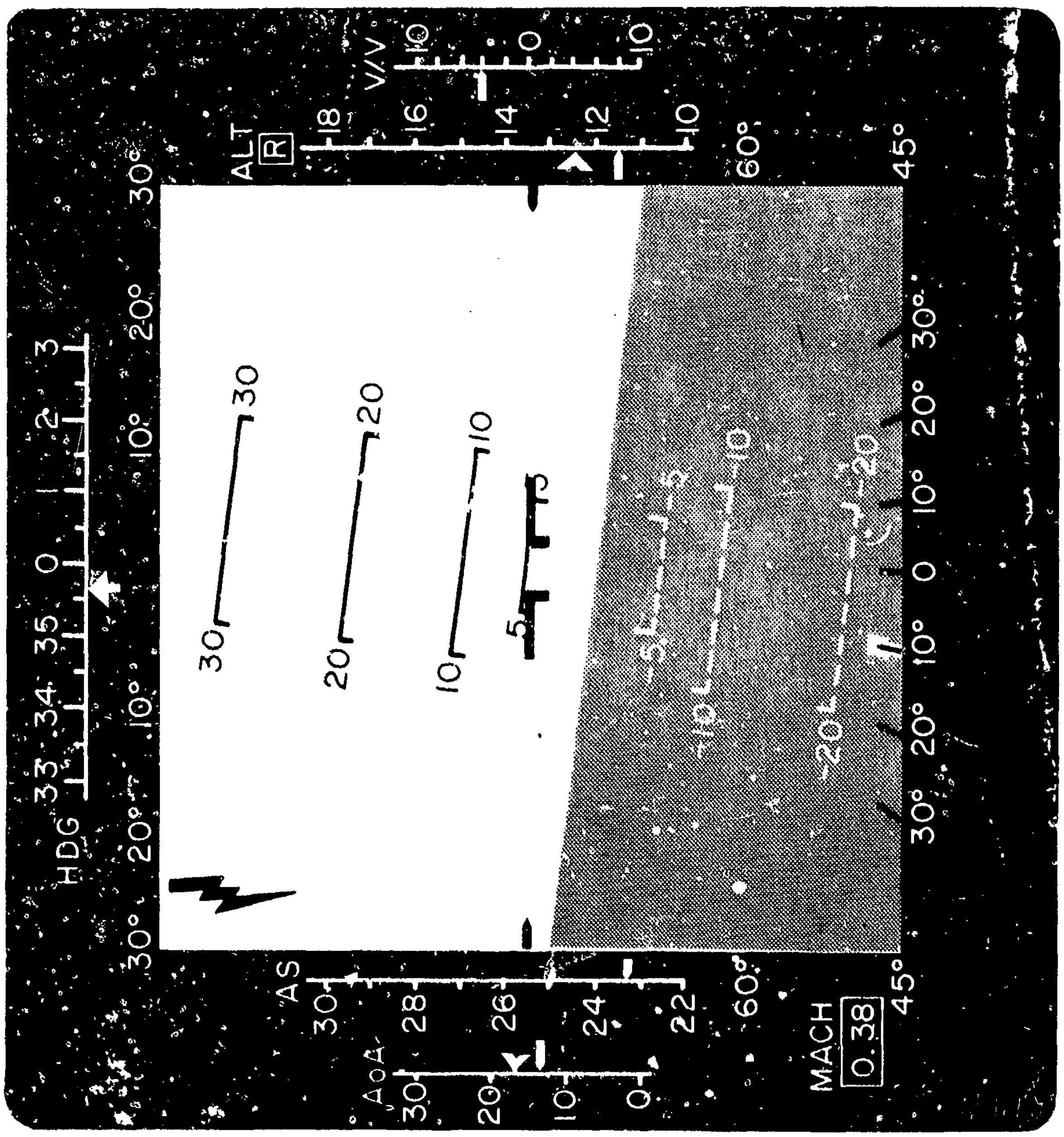


FIGURE 52

VDS FORMAT LANDING MODE

FIGURE 53

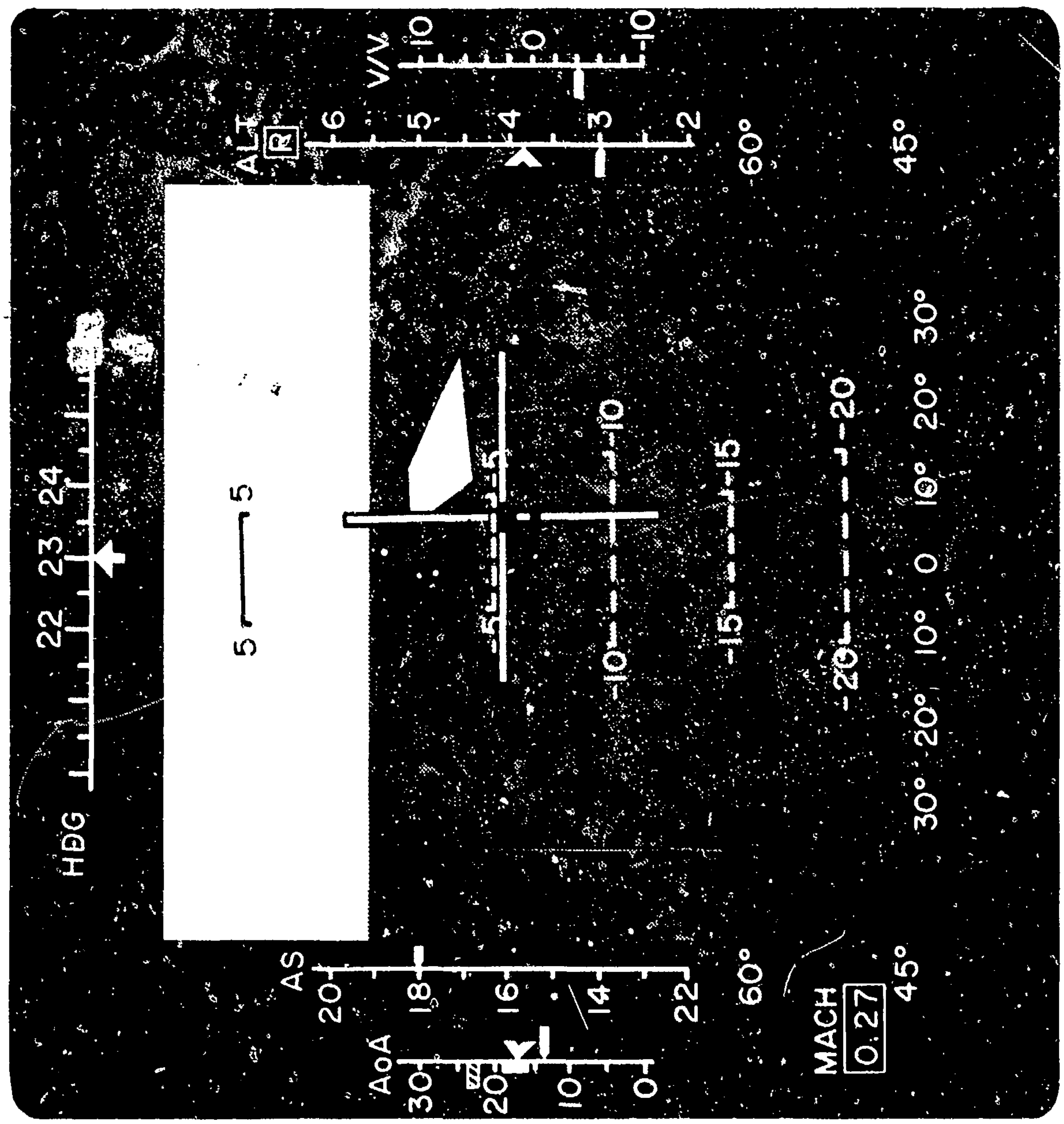


FIGURE 53

TABLE 33

DYNAMIC SIMULATION FORMAT

PARAMETER	LOCATION (1)	CHARACTER SIZE (2)	SCALE TYPE	EXCEPTIONS (3)
HEADING	Top Center	.284"X.187"	Fixed Pointer, Sliding Scale .5° Resolution, 40° Visible at Any Time.	Characters Large Command Pointer Constrained to Integer Multiples of 10°.
MACH	Lower Left	.284"X.187"	--	Characters Large. Range Limited to 0.96. 0.02 Resolution.
AIR SPEED	Left	.284"X.090"	Folding Scale, Moving Pointer. Scale Markings at 20 Knot Intervals. Scale Length is 80 Knots.	Unusual Character Size. Resolution Limited to 5 Knots. Actual and Command Pointers Not Bold Enough. No Hysteresis at Folds of Scale. 640 Knot Range.
ALTITUDE	Right	.284"X.090"	Similar to Airspeed 8000 Ft. Scale Length	Similar to Airspeed 500 Foot Resolution, Except 50 Foot Resolution Under 500 Feet. 64,000 Foot Range.
ANGLE OF ATTACK	Far Left	.250"X.140"	Fixed 0-30 Scale Sliding Command and Actual Pointers	
VERTICAL VELOCITY	Far Right	.230"X.125"	Fixed 10-0-10 Scale Sliding Command and Actual Pointers	
PITCH	Center	.284"X.187"	Ladder In 10° Increments, 1° Resolution.	Characters Large. Horizon Reference "Feet" Omitted. Negative Increments were not Dashed. +30° to -30° Range.
ROLL	Center and Bottom	.209"X.125"	Rolling Horizon and Pitch Ladder. Moving Indexer and Fixed Scale at Bottom of Display.	Characters Small. Roll Indexer Considerably Small. +22.5° to -22.5° Range. 2.5° Resolution.

TABLE 33 (Continued)

NOTES:
1) Refer to figure
2) Character size chosen to span recommended size. Size of moving or changing characters dictated by available fonts of display generator.
3) Exceptions are deviations from the design formats as previously discussed. Exceptions were dictated by hardware and software limitations.

8.6.3 Dynamic Simulation Results

The results of the dynamic simulation testing, in general, supported the conclusions reached in the study phase of the VDS design. The simulation was valuable in obtaining the comments and criticisms of eight qualified observers and in gaining the programming experience necessary for a preliminary design of the hardware and software required in the VDS system. The detailed results and conclusions will be discussed in the two following sections.

8.6.4 Questionnaire Results and Observer Comments

The eight qualified observers who viewed the simulation completed a brief questionnaire. An interview was held with each observer to obtain more detailed comment on the simulation performance. This section will summarize the answers given on the questionnaire and include pertinent comments from the interviews.

The first two questions pertained to the size and shape of the alphanumeric characters. The purpose of these questions was not to obtain quantitative human factors data on character perception. The purpose was to determine the resolution required in the symbol generater and symbol memory of the VDS system. The simulation formats include six sizes of characters ranging in height from .18 inch to .29 inch. Six different fonts were used, ranging from 6x7 to 9x12 matrixes. The dot size was varied so that the increase in font complexity did not necessarily result in a proportional increase in size.

The observer's answers indicated that a character height of 0.25" or larger is acceptable for the VDS formats. The preferred fonts were either 9x11 or 10x12 dot matrixes. These fonts have sufficient resolution to allow adequate distinction between all required symbols.

The third and fourth questions were on the acceptability of the format and placement of the scales around the border of the display. In general, the location of the scales was acceptable. Some criticism was received on the close spacing of the scales at the sides of the display. However, the observers unanimously declared the airspeed and altitude scale formats to be unacceptable. These scales were implemented with a "folded" scale and a

moving pointer. When the pointer reached either end of the scale, the scale numerals were changed and the pointer jumped to the other end of the scale. This technique required the observers to search for both the scale factor and the pointer and was unacceptable. The majority of the observers recommended an implementation with a fixed pointer and a continuously moving scale. This technique was used for the heading scale. The vertical velocity and angle of attach scales were acceptable, though possibly lacking in resolvability, particularly in the landing mode.

Questions five and seven dealt with the quality and contrast of the video image. The images were considered acceptable in both the raster and simulated-dot-matrix displays, even though the image quality was not as good as the quality of the display on the 525 line monitor. One pertinent comment was that increasing the brightness of the scale indexers would allow the observer to acquire the scale values more rapidly.

Question six was on the general quantity of information present in the formats. The take-off-and-cruise mode was acceptable to all observers in presenting all information required without including any unnecessary or redundant data. However, two reasonable objections were raised to the landing formats. The first was that the angle-of-attack could not be read to the required accuracy on the existing scale. The suggested solutions to this problem were to either expand the scale or to eliminate the Mach number in the landing mode and replace it with a digital readout of angle of attack. The second objection dealt with the display of the instrument landing parameters. The display included a velocity vector dot and a cross indicating the correct velocity vector. When these two are aligned, the aircraft is on the correct glide path. This was considered an acceptable landing indicator. However, the recommended format also included an artificial runway symbol which was not used during the simulation. Since the landing approach to an aircraft carrier is essentially a straight line flight, only two, not three, references are required to locate the correct glide path. Two observers strongly felt that the third symbol was redundant and tended to clutter the display. No conclusions were reached as to which two symbols would be preferred.

The last questions were on the quality of the alphanumeric and graphic image in the center of the display, including the artificial horizon, pitch ladder, aircraft symbol and roll attitude reference. The general agreement was that the information was acceptable. Two very important conclusions can be drawn from the comments to these questions. The first is that the horizontal line-segment approximations to diagonal lines that were used in the horizon and pitch ladder are completely acceptable. Several of the observers even felt that the stepped horizon line was preferable and more realistic than a straight diagonal line. The second conclusion is that the stepping of the images caused by the five hertz display update rate was not totally unacceptable. While five observers indicated that the jumping of the horizon and pitch ladder was disconcerting, all observers agreed that they could fly the aircraft with the display as presented.

The generalized conclusions that may be drawn from the results of the dynamic simulation are as follows:

1) The information-requirements analysis for the take-off and cruise mode and landing mode was correct.

2) The two VDS formats simulated are acceptable with the exceptions of the airspeed and altitude scales. Changing these scales as recommended and relocating the scales at the sides of the display would result in a VDS completely compatible with recent Navy HUD designs.

3) While a five hertz display update rate is marginally acceptable, ten hertz would appear to be the preferred update rate. There is no indication that continuous (i.e. 30 hz) update is required. Note that update rate, that rate at which the total image is changed, should not be confused with refresh rate which would be 60 hz in all cases.

4) The data obtained from the questions on the character sizes and fonts and the lack of objection to the approximated diagonal lines indicates that 400x400 resolution is adequate for the alphanumeric/graphic portions of the VDS images. This does not imply that 400 line resolution is anywhere nearly adequate for the sensor images. This requirement is best fulfilled by the use of 806x806 active line which is compatible with 875 TV-line scanning standards.

8.6.5 Programming Considerations

The programming of the dynamic simulation provided some insight into the hardware-software package required for the VDS system. The programming for the simulation required 2415 words of computer storage. 240 words were used for routines to input and interpret instructions from the teletypewriter and to calculate the aircraft situation. This programming will not be required in the final VDS system, since the aircraft will already contain some form of air-data-computer. 370 words of programming were required to do diagonal vector generation. In the final VDS system, this task will be assigned to hardware in the symbol generator. An additional 120 words of storage can be eliminated if the pitch and roll angle data is available in trigonometric form (sine and cosine, preferably).

The software used in the simulation was the first attempt at the problem. Experience indicates that rewriting the software to minimize the number of instructions should result in an additional 15% reduction.

Thus the programming required to generate the take-off, cruise and landing formats will require 1450 words of storage.

$$\begin{array}{r} 2415 \\ -240 \\ -370 \\ -120 \\ \hline 1685 \\ \text{X}.85 \\ \hline 1442 \end{array}$$

These 1450 words will include the programming to generate the air-data portions of all the formats.

Based on this information and the complexity of the other required formats, the following estimates of computer size can be made:

Computer Size Estimates For VDS System:

Word Length:	16 Bits
Number of Arithmetic Registers:	4 minimum
Number of I/O Channels:	8 minimum including one multiplexed channel
Number of Words of Program (Read-Only) Storage:	4096
Number of Words of Working-Area (Read-Write) Storage:	1024

9.0 DIGISPLAY SYSTEM TRADEOFF ANALYSIS

In Section 6 of this report it was concluded from an evaluation of non-CRT display techniques that the Northrop-developed DIGISPLAY is one of the two most promising candidates for meeting the VDS requirements identified in Section 3. This conclusion along with Northrop's intimate familiarity with DIGISPLAY technology has prompted the selection of the DIGISPLAY as the example to be used for the VDS baseline design. A brief description of the DIGISPLAY is given in Appendix A3.

In designing a high performance display such as is required for the VDS, it is important that some optimization of the more significant parameters be performed so as to make this high performance realizable. Generally it will be found impossible to optimize all parameters simultaneously, however, since their interdependence may result in conflicting requirements. In such a situation a tradeoff analysis is in order whereby the best compromise among all the alternatives can be identified and offered as the optimum overall design.

A computer-aided tradeoff analysis was subsequently performed for the purpose of evaluating the suitability of various DIGISPLAY designs for the VDS application. The computer made it possible to perturbate various parameters and to observe their effect on display performance with little chance for arithmetical error. Sections 9.1 and 9.2, which follow, describe the system input parameters which were assumed, the parametric equations which were solved and the concluding results which were obtained. Although no selection of the optimum configuration is made here (see Section 10 for this design selection), the assets and liabilities of each of the configurations analyzed are identified and some discussion is given with regard to their implications.

9.1 COMPUTER PROGRAM FOR DIGISPLAY OPTIMIZATION

The realization of high performance VDS operation necessitates the optimization of the display's design parameters. This optimization, however, must be performed through a parametric tradeoff analysis since the interdependence of many parameters precludes their optimization singly.

As an aid in performing this parametric tradeoff evaluation, a FORTRAN computer program was written and used to solve the various mathematical equations of physics which govern the performance of the DIGISPLAY system. Although these equations were not in themselves particularly difficult to solve by hand, their solution by computer greatly reduced the time and labor involved in evaluating many of the possible DIGISPLAY configurations which were promising candidates for the VDS. Furthermore, the computer program was far less prone to arithmetical error, error which if undetected could easily have procreated incorrect conclusions.

Although analytical techniques such as computer programming are powerful tools for analysis, they are generally relatively weak for synthesis. For example, given a list of independent input parameters such as voltage, current, dwell time, etc., a computer can readily analyze a dependent output parameter such as screen brightness. However, if a desired dependent parameter such as screen brightness is given instead, the computer is nearly incapable of synthesizing the independent parameters which collectively result in the desired dependent parameter. Unfortunately, optimization implies synthesis and not analysis. Therefore it was not possible to write a computer program which, when given the desired performance parameters such as brightness, power, contrast, etc., would synthesize the DIGISPLAY configuration and operational parameters which were optimum in achieving this result. Instead, it was necessary to write a program which, when given a DIGISPLAY configuration and suitable operational parameters, would analyze its expected performance. A sense of optimization could be achieved then only by analyzing many configurations and subsequently choosing that configuration which most nearly met the desired performance parameters.

The following paragraphs will describe the computer program in some detail with emphasis on the mathematical equations which it solves. In Table 34 a list of the input parameters necessary to run the program is given. Most of the parameters were held constant from one computer run to the next so as to make a comparison between various DIGISPLAY configurations meaningful. The values of these constant parameters are also listed. All of the values listed under the heading of "Physical Parameters" represent the state-of-the-art in DIGISPLAY design. Those listed under "Operational Parameters" and "Electronic

TABLE 34 COMPUTER PROGRAM INPUT PARAMETERS

SYMBOL	PARAMETER	VALUE IF HELD CONSTANT
	PHYSICAL PARAMETERS	
$1/S$	Hole Resolution	80 Holes/inch
D	Hole Diameter	6.5 Mils
X_p	Plate Thickness	4.0 Mils
X_s	Spacer Thickness	4.0 Mils
G	Conductor Gap (minimum)	2.5 Mils
K_p	Plate Dielectric Constant	6.95
K_s	Spacer Dielectric Constant (average)	2.5
η	Input Buffer Segments	8
	OPERATIONAL PARAMETERS	
V_{on}	Plate Voltage (on)	90 Volts
V_{off}	Plate Voltage (off)	-30 Volts
$1/\tau_{frame}$	Frame Rate	30 Hertz
ζ_p	Phosphor Luminous Efficiency (P-44)	410 Ft-L/μA/cm^2 @ 10 KV
V_{phos}	Phosphor Voltage	10 KV
	Phosphor Burn Parameter (P-44)	100 Coulombs/cm^2
N_I	Scan Interlace	2:1
V_{cup}	Flood Gun Cup Voltage	5 Volts
V_{screen}	Flood Gun Screen Voltage	22 Volts
V_{input}	Stack Input Voltage	25 Volts
V_{mod}	Maximum Modulation Voltage	40 Volts
m	Typical Modulation Depth	0.2
R	Plate Switching Rate	Variable

TABLE 34 COMPUTER PROGRAM INPUT PARAMETERS (CONT'D)

SYMBOL	PARAMETER	VALUE IF HELD CONSTANT
	ELECTRONIC PARAMETERS	
P_h	Heater Requirement	75 mw/cm^2
ζ_{gun}	Flood Gun Current Efficiency	0.25
P_1	Logic Circuitry Power	25 mw/driver
a	Driver Bias Factor	0.1
P_{quies}	Driver (Modulator) Quiescent Power	200 mw/driver (Modulator)
N_v, N_h	Display Format	Variable
N_p	Number of Plates	
N_L	Number of leads per Plate	
K_L	Length of Plate Finger in #holes	
K_w	Width of Plate Finger in #holes	
N_b	Number of Scanning Beams	

Parameters" represent typical values which may be expected with an operational DIGISPLAY system. Most of these values have been obtained or extrapolated from prototype DIGISPLAY devices which are presently in laboratory development.

Lead Capacitance - One significant parameter which is strongly configuration dependent and which affects DIGISPLAY performance is the lead capacitance of the various decoding and modulator plates of the DIGISPLAY configuration. The lead capacitance has a direct influence on the speed at which a plate may be switched and therefore also has a marked influence on the scanning beam dwell time available.

The total lead capacitance may be subdivided into three parallel components: an inter-plate gap capacitance, C_s, an intra-plate gap capacitance, C_p, and an inter-hole capacitance, C_h. The equations which define each of these three components are derived in Appendices A4, A5, and A6, respectively. Here we will merely indicate the results:

$$C_s = 2K_s \epsilon_o \frac{K(k_1)}{K(k_1')} \left(SK_L\right)$$

$$C_p = K_p \epsilon_o \frac{K(k_2')}{K(k_2)} \left(SK_L\right)$$

$$C_h = K_p \epsilon_o \frac{1}{1 - \frac{1}{\pi} \ln\left[2 \sin\left(\frac{\pi D}{2S}\right)\right]} \left(X_p K_L\right)$$

where K(k) is the complete elliptic integral of the first kind for modulus k, and

$$k_1 = \frac{\tanh\left[\frac{\pi SK_w}{4X_s}\right]}{\tanh\left[\frac{\pi(SK_w + 2G)}{4X_s}\right]} \qquad \text{with } k_1' = \sqrt{1-k_1^2}$$

$$k_2 = \frac{\tanh\left[\frac{\pi G}{2X_p}\right]^{1/2}}{\tanh\left[\frac{\pi\left(SK_w + G\right)}{2X_p}\right]^{1/2}} \qquad \text{with } k_2' = \sqrt{1-k_2^2}$$

The total lead capacitance may then be written as:

$$C_L = K_g\left(C_s+2C_p\right) + C_h$$

where the constant K_g is dependent upon the actual geometry of the interdigital conductor fingers on each plate. Comparison of the capacitance values calculated from this equation with those measured on actual decoding plates indicates that for most decoding plates K_g is approximately 0.825 but for modulator plates and those decoding plates which are similar to modulation plates (i.e., have conductor fingers which are only one-hole wide), K_g is very nearly unity.

Access Time - As mentioned previously, the limit on plate switching speed, or display access time, is governed by the lead capacitance (and to a lesser extent the switching voltage) of each decoding or modulator plate. High lead capacitance requires a long access time to permit all switching transients to stabilize. Consequently low lead capacitance is desirable although high lead capacitance is tolerable on some plates if they are required to switch either not too often or only at appropriate times such as the end of a line or the end of a field.

Two high voltage switch designs have been fabricated and tested for previous programs. Switch number 1 was designed some time ago under a Northrop IR&D program to drive a 512-character alphanumeric DIGISPLAY. Switch number 2 was designed more recently under AFAL Contract F33615-70-C-1188. A third switch has been fabricated and tested during the past few months for the VDS program. The switching performance of each of these three switches as a function of capacitive load is illustrated in figure 54. Note that the access time is approximately linearly proportional to load capacitance for all values in excess of a few hundred picofarads. At the lower capacitive loads the storage capacity of the switch itself become the dominant factor.

A mathematical curve-fit to the performance of Switch number 3 was written into the computer program to account for this dependence of access time on capacitive load. The following equation fits the performance curve of Switch number 3 well:

$$\tau_a = 5 \times 10^{-8} + 3 \times 10^{-10}\ C_L$$

where C_L is in picofarads and τ_a is in seconds.

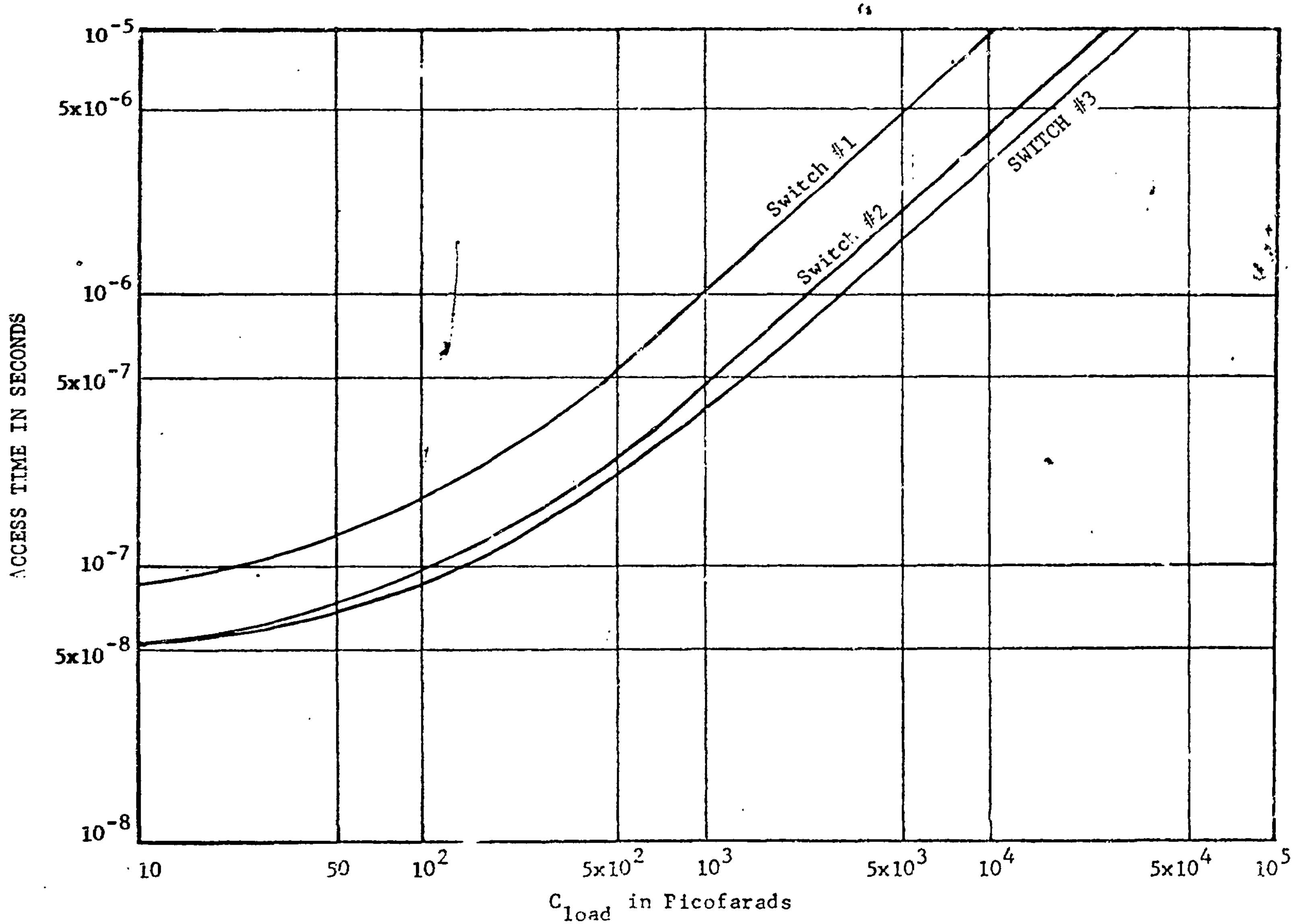


FIGURE 54 ACCESS TIME VERSUS LOAD CAPACITANCE

Screen Brightness - As presently written, the computer program permits a calculation of the DIGISPLAY's screen brightness in any one of four different operational modes. The first two modes pertain to a display without storage, the first being with conventional horizontal and vertical blanking periods and the second without. Because the time required to switch beam position in the DIGISPLAY is virtually independent of the distance moved, vertical and horizontal blanking periods to allow for sweep flyback are not required as they are for the conventional CRT. The only reason for their inclusion in the computer program is to allow for compatibility with sensors or scan conversion tubes which do require this blanking.

The last two modes are similar to the first two except that the inclusion of a storage target is assumed. The flood and erase functions are performed during the vertical blanking periods only when conventional TV compatibility is desired. When compatibility is not required, the flood and erase functions are performed immediately after a complete field of information is written. Only the third mode will be described here as it provides a high brightness display which is compatible with conventional TV formatting and is therefore most suitable for the VDS.

The computer program first calculates the maximum dwell time available for writing the storage mesh from the following equation:

$$\tau_{dwell}(\max) = \frac{N_b}{N_h}\left[\frac{\tau_{frame} - N_I(1.25\ \text{ms})}{N_v} - 7\ \mu s\right] - \tau_a$$

where the Electronic Industries Association (EIA) standards* of 1.25 ms and 7 μs are allotted for the vertical and horizontal blanking periods, respectively. The integers N_v and N_h are the number of holes (resolution elements) in the vertical and horizontal directions, respectively, and N_b is the number of simultaneously scanning write beams. N_I is the interlace factor (e.g., $N_I = 2$ for a conventional 2:1 interlace).

*See EIA Standard RS-343A, "Electrical Performance Standards for High Resolution Monochrome Closed Circuit Television Camera," Electronic Industries Association, Washington, D.C., September 1969.

The flood gun current density necessary to charge the storage mesh is then calculated from

$$J_{input} = \frac{Q_{min}\,\tau_{dwell}}{\beta\, T_{stack}}$$

where β is an aperture correction factor which has been assumed to be two in order to account for some focusing of the flood gun current into the holes of the decoding stack, T_{stack} is the effective electron transmission of the stack, and Q_{min} is the minimum charge density necessary to charge the storage target. This minimum charge density is on the order of 10^{-8} coulombs per square inch with present day technology and this value which has been confirmed by laboratory measurement was used in the program. Substantial increases in charge storage performance can be expected in the near future, however.

The stack transmission is a function of the ratio of the length, L, of the holes through the stack to their diameter, D. This transmission has been measured on previous DIGISPLAY devices and these data are illustrated in figure 55 Note that although no electron multiplication occurs within the stack itself, a transmission higher than unity can be achieved with very short (L/D less than 3) stacks due to the previously mentioned focusing effects at the stack input. A mathematical curve fit used by the computer program to account for stack transmission is

$$T_{stack} = \frac{2.7}{L/D - 0.84}$$

The total flood time available per frame is then calculated as the difference between the vertical blanking periods and the sum total of the erase times and the storage mesh access times, i.e.,

$$\tau_{flood} = N_I(1.25 \text{ ms} - \tau_{erase} - 3\,\tau_{store})$$

Note that τ_{flood} is the total flood time per frame and that with a 2:1 interlace scheme this flood time would be equally divided into two flood periods, one at the end of each field.

Experimental evidence has indicated that the erase time, τ_{erase}, must be approximately 100 times longer than the minimum dwell time. This indication was also incorporated into the computer program.

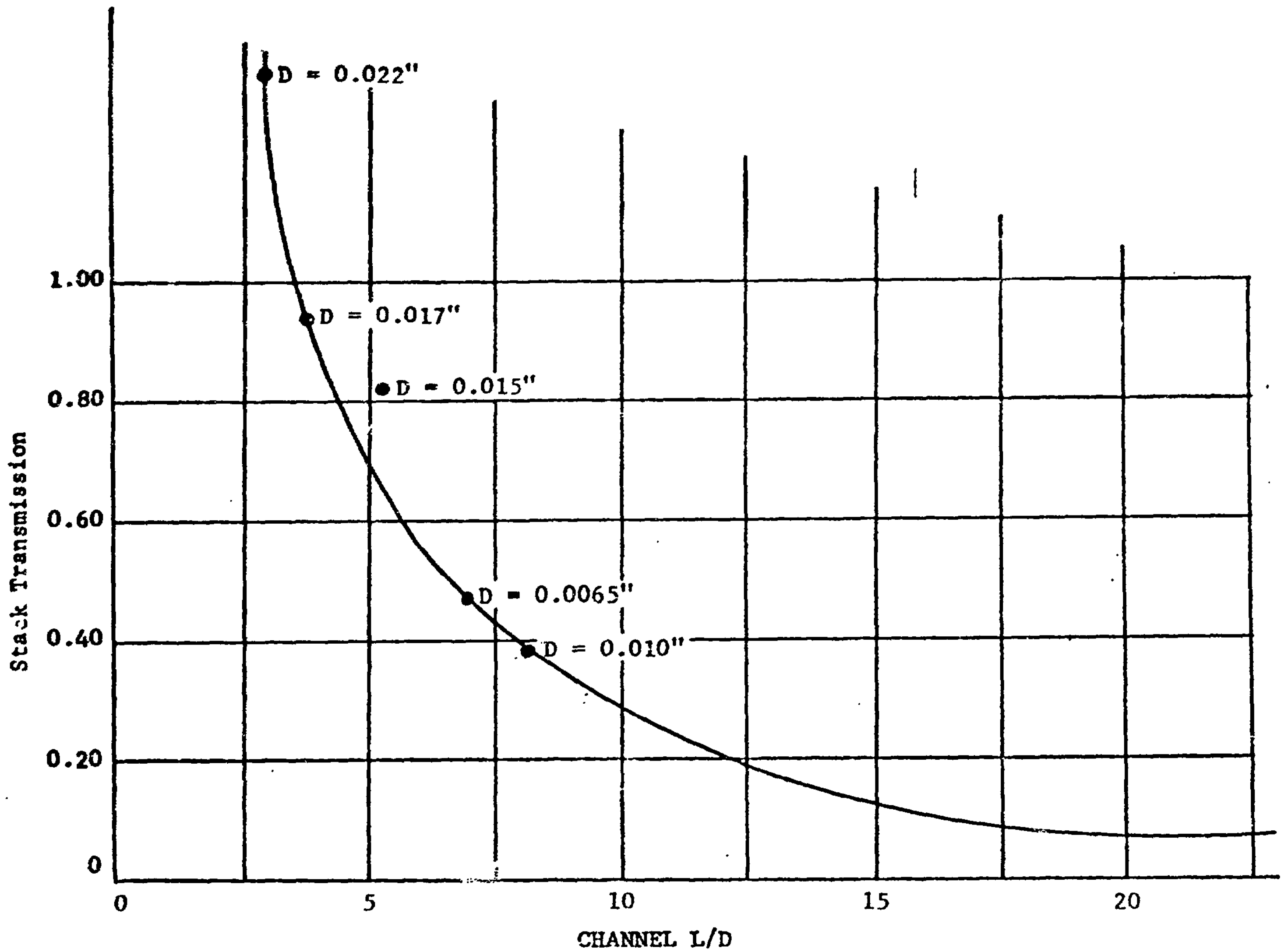


FIGURE 55 MEASURED DIGISPLAY STACK TRANSMISSION VERSUS CHANNEL LENGTH TO DIAMETER RATIO FOR VARIOUS CHANNEL DIAMETERS

The storage mesh access time, τ_{store}, was calculated from the following relation

$$\tau_{store} = C_{store}\left(\frac{V_s}{I_s}\right)$$

where V_s is the maximum voltage swing encountered in switching from write to flood (assumed to be 300 volts) and I_s is the maximum charging current available to perform the switch (assumed to be 200 milliamps). The storage mesh capacitance was assumed to be the parallel-plate capacitance between the storage mesh and the collector plate on one side and the contrast enhancement plate on the other, i.e.,

$$C_{store} = 2\,K_s\,\epsilon_0\left(\frac{N_v\,N_h\,S^2}{X_s}\right)$$

The factor of 3 multiplying τ_{store} in the equation for the total flood time is to account for the three switching operations which occur at the end of each field, namely the switch from write to flood, the switch from flood to erase, and then the switch from erase to write again.

The time-average current density striking the phosphor screen as a result of image flooding is then calculated as

$$J_{phos} = 0.8\,\beta\,J_{input}\,T_{stack}\,T_{store}\left(\frac{\tau_{flood}}{\tau_{frame}}\right)$$

where the 0.8 factor accounts for the fact that the input current density was chosen to provide 80 percent full brightness and T_{store} is the electron transmission of the storage target. T_{store} was assumed to be 0.1 in the computer program since laboratory experience has indicated that this value is readily obtainable with commercially available storage targets. There is every reason to believe, however, that storage mesh transmission could be substantially increased if the proper development effort were placed in this area.

Finally the DIGISPLAY screen brightness is calculated as:

$$B_{screen} = J_{phos}\,\xi_p\left(\frac{\pi D^2}{4S^2}\right)$$

where ξ_p is the phosphor's luminous efficiency at the desired phosphor potential (in this case at 10 kilovolts). The factor in parentheses accounts for the fact that the DIGISPLAY creates a dot matrix image consisting of bright dots on a dark background. Hence the screen brightness is less than the spot brightness by a factor equal to the ratio of the area of the spot to the area of a resolution element. In DIGISPLAY devices the screen brightness will typically be four to five times less than the spot brightness.

At this point it is worth saying something about phosphor screens especially with regard to phosphor life at high brightness. The light output of all phosphor screens decay with time, some quite rapidly and others more slowly. This phosphor fatigue is generally due to either thermal burn or electronic aging. A brief discussion of phosphor life under high brightness operation is given in Appendix A7 where a side-by-side comparison of a number of high brightness phosphors is made. Of these phosphors, two relatively new rare-earth types, the P-43 and the P-44, are the most attractive for high brightness operation such as may be required of the VDS, and of these two the P-44 is preferable because its very narrow-band emission permits the employment of spectral filtering to achieve highly efficient contrast enhancement in spite of a high ambient illumination environment.

The P-44 is reputed to have a luminous efficiency of 44 lumens per watt excitation which corresponds to 410 foot-Lamberts per microamp/cm^2 at a 10 kilovolt excitation. Furthermore, the P-44 exhibits negligible current saturation in sharp contrast to the more common P-31 phosphor which has been used quite extensively in the past. And lastly, the P-44 is reputed to exhibit a high resistance to electronic aging being characterized by a coulomb rating in excess of 100 coulombs per square centimeter.

The computer program assumed the use of the P-44 phosphor because of the above mentioned benefits. Because of the accelerated research which is being done on phosphors at present, there is every reason to expect that even better materials will be developed within the next few years.

<u>Inherent Contrast Ratio</u> - Ideally, no beam current would flow from those channels which are biased off by one or more decoding plates. In practice, however, beam cutoff in actual DIGISPLAY devices is not perfect and minute

currents, called "ghost" currents, do flow from all channels in addition to the "on" beam current from the desired few. These ghost currents result in a reduction of image contrast and therefore must be kept to a minimum.

The magnitude of a ghost beam may be classed according to the number of decoding plates in the cutoff state it encounters in traveling from the input to the output of the decoding stack. For example, a first-order ghost is cut off by only one decoding plate in the stack, a second-order ghost by two, and so on. With this classification scheme it is obvious that the highest order ghost a stack consisting of N decoding plates can have is an N-th order ghost. It is also obvious that a first-order ghost is of greater consequence than a second and that a second-order ghost is of greater consequence than a third, and so on.

It can be shown that for a DIGISPLAY consisting of N_p nonredundant decoding plates and N_b multiple scanning beams, the number of first-order ghost associated with each scanning beam is

$$C_1 = \sum_{j=1}^{N_p} \left(n_j - 1\right)$$

when n_j is the decoding factor of the j-th decoding plate. For equally segmented decoding plates such as are normally used in DIGISPLAY devices, the decoding factor of a plate is equal to the number of decoding segments or leads on that plate. Thus the decoding factor of a binary plate is two but that of an 8-lead plate is eight.

Similarly, it can be shown that the number of second-order ghosts associated with each scanning beam is

$$C_2 = \sum_{j=1}^{N_p} \sum_{k \neq j}^{N_p} \left(n_j - 1\right)\left(n_k - 1\right)$$

where the (j,k) are all of the $\binom{N_p}{2}$ unordered pairs that may be chosen from the numbers $1,2,3,\ldots N_p$. Following the same procedure, the number of third-order ghosts associated with each scanning beam is

$$C_3 = \sum_{j=1}^{N_p} \sum_{k \neq j}^{N_p} \sum_{\ell \neq j,k}^{N_p} \left(n_j - 1\right)\left(n_k - 1\right)\left(n_\ell - 1\right)$$

where the (j,k,ℓ) are all of the $\binom{N_p}{3}$ unordered groups of three numbers that may be chosen from the numbers 1, 2, 3, ...N_p. The number of higher order ghosts associated with each scanning beam are calculated similarly.

Although it is not readily apparent, it may be reasoned that if a scanning beam has C_1 first-order ghosts, C_2 second-order ghosts, and C_i i-th order ghosts, then every position this beam scans will be a first-order ghost C_1 times, a second-order ghost C_2 times, and an i-th order ghost C_i times during every scan cycle. Hence, the sum of all the ghost currents yields the total ghost current emerging from each channel per scan cycle. If T_c is now the electron transmission of a single decoding plate when in the "cutoff" state and T_g is likewise but for the "gain" state, then the total ghost current per scan cycle is

$$I_g = I_i \sum_{i=1}^{N_p} \left(T_c\right)^i \left(T_g\right)^{N_p - i} C_i$$

where I_i is the input current to each channel in the stack.

We will now define the inherent contrast ratio of a DIGISPLAY device as

$$CR = \frac{I_b + I_g}{I_g}$$

where, $I_b = I_i \left(T_g\right)^{N_p}$ is the "on" beam current. Substituting the previous equation for the ghost current into this relation then yields

$$CR = \frac{1 + \sum_{i=1}^{N_p} \left(\frac{T_c}{T_g}\right)^i C_i}{\sum_{i=1}^{N_p} \left(\frac{T_c}{T_g}\right)^i C_i}$$

where the ratio of T_g to T_c is called the gain-to-cutoff ratio of the decoding plate. The gain-to-cutoff ratio is a function of the magnitude of the switching voltage applied to each decoding plate and has been found to be as high as 10,000 for a moderate switching voltage of only 120 volts.

The computer program calculates the number of first, second, third, etc., order ghosts and the inherent contrast ratio as a function of the gain-to-cutoff ratio in accordance with the above equations.

Input Power - The computer program was written to also provide an engineering estimate of the total input power necessary to operate the DIGISPLAY. This power is dissipated in six basic areas, three of which are internal to the DIGISPLAY tube itself. These three are heater power for the flood gun cathode, beam power dissipated in the flood gun structure and decoding plate stack, and beam power dissipated in the phosphor screen. The three external losses are quiescent power dissipated in the scan logic circuitry, reactive switching power dissipated in the decoding plate switch circuitry, and reactive power dissipated in the modulator circuitry. Estimates of the power loss in each of these areas are given in the following paragraphs.

The required flood gun heater power has been assumed to be proportional to the size of the display but to be essentially independent of the magnitude of the current emitted. Hence a space-charge limited flood gun has been assumed. The required heater power is then

$$P_{heater} = \left(N_v N_h S^2\right) P_h$$

where the quantity in parentheses indicates the display size and P_h is an experimentally determined normalization factor indicating the input power required per unit area. For all of the computer runs made P_h was assumed to be 75 milliwatts per square centimeter, a number which was empirically derived from a prototype 512x512 DIGISPLAY.

The beam power dissipated in the flood gun structure and the decoding plate stack is dependent upon the voltage on and the current collected by each element. The major current collecting elements are the flood gun cup, the flood gun screen, and the stack input buffer plate. With V_{cup}, V_{screen}, and V_{input} the voltages on the cup, the screen, and the input buffer, respectively, and with ξ_{gun} the current efficiency of the flood gun, the division of

current among these three elements has been experimentally found to follow the following relations:

$$J_{cup} = J_{total}\left(1 - \xi_{gun}\right)\left[2\left(\frac{V_{cup}}{V_{screen}}\right)^2\right]$$

$$J_{screen} = J_{total}\left(1 - \xi_{gun}\right)\left[2\left(\frac{V_{cup}}{V_{screen}}\right)^2 + 1\right]$$

$$J_{input} = J_{total}\,\xi_{gun}$$

where J_{total} is the total effective emission current density available. These empirical relations apply to a flood gun which is similar in design to that developed for a 512x512 DIGISPLAY.

The beam power dissipated may then be written as

$$P_{beam} = \left[(JV)_{cup} + (JV)_{screen} + (JV)_{input}\right]\left(N_v N_h S^2\right)\left[\frac{\tau_{flood} + \tau_{erase}}{\tau_{frame}} + \frac{1}{\eta}\left(1 - \frac{N_I(1.25\ \mathrm{ms})}{\tau_{frame}}\right)\right]$$

where the middle term in parentheses is the size (area) of the display and the last term in brackets indicates the fractional time during which the flood gun is unblanked, i.e., during the flood, erase, and write periods. The integer η represents a spacially selective blanking of the beam during the write period which may be implemented by segmenting the flood gun screen or input buffer plate. This selective blanking was assumed throughout the tradeoff analysis by setting η equal to eight.

The beam power dissipated by the phosphor screen is dependent upon the information displayed. However, in the worst case of maximum screen brightness this power may be estimated as

$$P_{phos} = J_{phos} V_{phos}\left(N_v N_h \frac{\pi D^2}{4}\right)$$

where J_{phos} is the time-averaged spot current density, V_{phos} the phosphor excitation potential, and the term in parentheses the total area of all the spots in the dot matrix display.

One of the external sources of power dissipation is the scan logic circuitry. For purposes of an engineering estimate it was assumed that the total logic power dissipated was proportional to the number of decoding plate leads which were required to be switched:

$$P_{logic} = \sum_{i=1}^{N_p} P_1 \left(N_L\right)_i$$

where the proportionality constant P_1 was assumed at 25 milliwatts per lead and $\left(N_L\right)_i$ is the number of leads contained by the i-th decoding plate.

The decoding switch driver and the modulator power dissipations are similar. They each consist of a transient dissipation which occurs every time they are switched and a quiescent dissipation. The defining equations were assumed to be of the form

$$P_{driver} = \sum_{i=1}^{N_p} \left(N_L\right)_i \left|(1+\alpha)R_i E_i + P_{quies}\right|$$

$$P_{mod} = \left(N_L\right)_{mod} \left|(1+\alpha)R_{mod}\, E_{mod} + P_{quies}\right|$$

where α is a switch bias factor (assumed to be 0.1), R_i is the switching rate of the i-th plate (a direct function of the display frame rate) and E_i is the energy required to switch the capacitive load representative of each lead of the i-th plate, i.e.,

$$E_i = \frac{1}{2}\left(C_L\right)_i \left|V_{on} - V_{off}\right|^2$$

$$E_{mod} = \frac{1}{2}\left(C_L\right)_{mod} \left|\alpha\, V_{mod}\right|^2$$

P_{quies} is the quiescent dissipation per switch or modulator which was assumed to be 200 milliwatts, a value derived from laboratory experience.

The computer program was written to calculate each of the six power dissipations described above and to determine the total input power required by the DIGISPLAY system as their sum:

$$P_{input} = \eta_p \left(P_{heater} + P_{beam} + P_{phos} + P_{logic} + P_{driver} + P_{mod}\right)$$

where η_p is the effective power conversion efficiency of the input power system. This efficiency was assumed to be a conservative 64 percent for the entire tradeoff analysis.

9.2 TRADEOFF ANALYSIS RESULTS AND CONCLUSIONS

The tradeoff analysis was restricted to display formats which are compatible with the EIA scanning standards for high resolution television. Of particular interest were the 875, the 945, and the 1023 lines per frame scanning standards since these three appear to be most compatible with the diverse system requirements characteristic of the VDS application. It is significant to note, however, that these scanning standards refer to the total number of scan lines per frame and not to the active number of scan lines per frame. It is customary to allot 7.5 percent of the total field period to vertical retrace; consequently, the number of active scan lines is approximately 7.5 percent less than the total number of scan lines. Therefore a dot matrix display, such as DIGISPLAY, need have only 809 rows of dots to satisfy the 875 standard, 874 rows to satisfy the 945 standard, and 946 rows to satisfy the 1023 standard. Because 809 is a prime number and is therefore not decodeable, only the 810x810, the 874x874, and the 946x946 DIGISPLAY formats were analyzed during this tradeoff evaluation. Of course, each of these formats may be decoded by the DIGISPLAY in several different ways some of which are more favorable than others.

<u>Configuration Selection</u>. The basic algorithm for selecting the possible decoding schemes for a DIGISPLAY device is

$$N_R = N_b \prod_{i=1}^{N_p} n_i$$

where N_R is the number of resolution elements (channel holes), N_b is the number of multiple scanning beams, and n_i is the decoding factor (an integer) of the i-th of N_p decoding plates. The most significant point which this algorithm emphasizes is that both the number of multiple beams and the decoding factors of each and every decoding plate <u>must</u> be an integer factor

of the number of resolution elements contained in the display. Conversely, if a particular number of multiple beams is desired, then the size of the display in terms of its number of resolution elements must be an integer multiple of the number of beams. Furthermore, this integer multiple must equal the product of the decoding factors of each and every decoding plate. Consequently, only certain decoding factors and certain numbers of multiple beams are admissible for a particular display of a given format.

The prime factors of an 810x810 display are $2\cdot3\cdot3\cdot3\cdot3\cdot5$ and therefore any one or combination of these factors is suitable as a decoding factor or as the number of multiple beams in this display. The prime factors of an 874x874 display are $2\cdot19\cdot23$ and those of a 946x946 display are $2\cdot11\cdot43$. Obviously there are less combinations possible with either the 874x874 or the 946x946 displays than there are with the 810x810 display. The possible combinations and therefore the possible number of multiple scanning beams with each of these display formats are listed in Table 35.

Each decoding factor requires one decoding plate for its implementation. An 810x810 format has six prime decoding factors and therefore it can have up to six decoding plates in each (horizontal and vertical) axis. Conversely the 874x874 and 946x946 formats each have only three prime factors and consequently may have only three decoding plates in each axis. Normally, however, it is desirable to have only two or three decoding plates in each axis because a large number of plates seriously reduces the current throughput efficiency of the DIGISPLAY plate stack and therefore necessitates higher input beam powers for a given display brightness.

The optimum decoding factors in terms of the least number of electronic switch circuits are those factors which are nearest to the N_p-th root of the number of resolution elements. For example, if we consider only one axis at a time, the optimum decoding factors for an 810x810 format with two plates in each axis are those factors which are closest to $\sqrt{810}$ (i.e., 27 and 30); with three plates in an axis the optimum decoding factors are 9, 9, and 10 since they are nearest to $\sqrt[3]{810}$. The optimum decoding factors for the 810x810, the 874x874, and the 946x946 formats are given in Table 36. Note that the best decoding factors for the last two formats are far less optimum than those for the 810x810 display.

TABLE 35

POSSIBLE DECODING FACTORS (OR MULTIPLE BEAMS) OF DIGISPLAY DEVICES

FORMAT	POSSIBLE DECODING FACTORS (OR MULTIPLE BEAMS)
810x810	1, 2, 3, 5, 6, 9, 10, 15, 18, 27, 30, 45, 54, 81, 90, 135, 162, 270, 405, 810
874x874	1, 2, 19, 23, 38, 46, 437, 874
946x946	1, 2, 11, 22, 43, 86, 473, 946

TABLE 36

OPTIMUM DECODING FACTORS OF SEVERAL DIGISPLAY DEVICES

FORMAT	1 PLATE Per Axis	2 PLATES Per Axis	3 PLATES Per Axis	4 PLATES Per Axis	5 PLATES Per Axis	6 PLATES Per Axis
810x810	810	27, 30	9, 9, 10	3, 5, 6, 9	3, 3, 3, 5, 6	2, 3, 3, 3, 3, 5
874x874	874	23, 38	2, 19, 23	--	--	--
946x946	946	22, 43	2, 11, 43	--	--	--

It is always possible to have the optimum decoding factors in at least one axis of the display. In the modulation axis, however, the decoding factors applicable are dependent upon the number of multiple beams desired since their product when multiplied by the number of beams must equal the format number in that axis. For example, if a 45-beam, 810x810 display is desired, the applicable decoding factors in the modulation axis must be integer factors of 18 since 18 times 45 equals 810.

It is obvious that there is a maximum to the number of multiple beams desirable. What this maximum is may be readily debated, but it seems certain that much over 100 beams would be greatly undesirable since a separate modulator is needed for each beam. Hence, we assumed that no configuration involving more than 100 multiple scanning beams was of further interest. Although less obvious, there is also a minimum to the number of multiple beams desired. If too few multiple write beams are used, there will be insufficient time during the write period to adequately charge the storage mesh prior to flooding. An estimate of this lower limit can be obtained from a consideration of the number of resolution elements which must be scanned during one complete frame period. Mathematically, this may be written as

$$N_b > N_R \frac{\tau_{min}}{\tau_{frame}}$$

where τ_{min} is the minimum beam stepping period deemed practical and τ_{frame} is the frame period. For a minimum beam stepping period of one microsecond the lower limit is from 20 to 30 beams for a format in the 800x800 to 1000x1000 range.

It was mentioned earlier that an 810x810 format can have up to six decoding plates in each axis whereas the 874x874 and the 946x946 formats are limited to only three in each axis because of the decoding factors appropriate to each case. Although the least number of leads and therefore the least number of electronic drive circuitry is obtained when the configuration employs the maximum number of decoding plates, such a configuration is most often quite unattractive for other reasons. To begin with, a large number of decoding plates necessitates higher input beam powers for a given display brightness due to a marked decrease in current throughput efficiency. Even more important, however, is that decoding plates with low decoding factors are invariably characterized by high lead capacitance. This high lead capacitance results in high power dissipation in

the electronic drive circuitry and in subsequent limitations on the maximum scanning speed capability of the display. It has been found from past experience that four or five plate designs with two or three plates in each axis exhibit considerably less lead capacitance at a modest penalty of only a few more conductor leads if the optimum decoding factors such as listed in Table 36 are used. This observation is illustrated in Figure 56 for the 810x810, the 874x874, and the 946x946 formats. Note especially for the 810x810 format that little is gained by employing more than five or six decoding plates. Because of the particular decoding factors of the 874x874 and the 946x946 formats, of course, these two cases can have no more than five or six decoding plates.

Another observation which can be made from Figure 56 is that far fewer conductor leads are required with the 810x810 format than are possible with either the 874x874 or the 946x946 formats due to a more favorable selection of decoding factors from which to choose. Hence, it may be said that the 810x810 format is inherently more suitable for DIGISPLAY implementation than the others because it is more readily decodeable.

Computer Results. A total of fifteen computer runs were made over the three formats selected for study. Eight computer runs were made for the 810x810 format because its favorable decoding factors resulted in many more possible configurations than either of the other two. Four and five plate 810x810 configurations having 30, 45, 54, or 81 multiple scanning beams were studied. Only three computer runs were made for the 874x874 format since its decoding factors did not permit any favorable five-plate designs and the number of multiple beams was limited to either 38 or 46. Four computer runs were made for the 946x946 format, all of them four-plate configurations having either 22, 43, or 86 multiple scanning beams.

The pertinent results of each of these computer runs are listed in Tables 37, 38, and 39. The various configurations in each table are identified by a code which describes the particular decoding scheme used. For example, the second configuration in Table 37 is listed as 27·30 x 18·(45). This particular code signifies a configuration which has a 27-lead and a 30-lead decoding plate in the vertical axis and an 18-lead decoding plate and a 45-lead (beam) modulator plate in the horizontal axis. Hence a dot is used to separate decoding plates in a single axis and an x is used to separate axes. Parentheses about a number signifies that that number refers to a modulator plate.

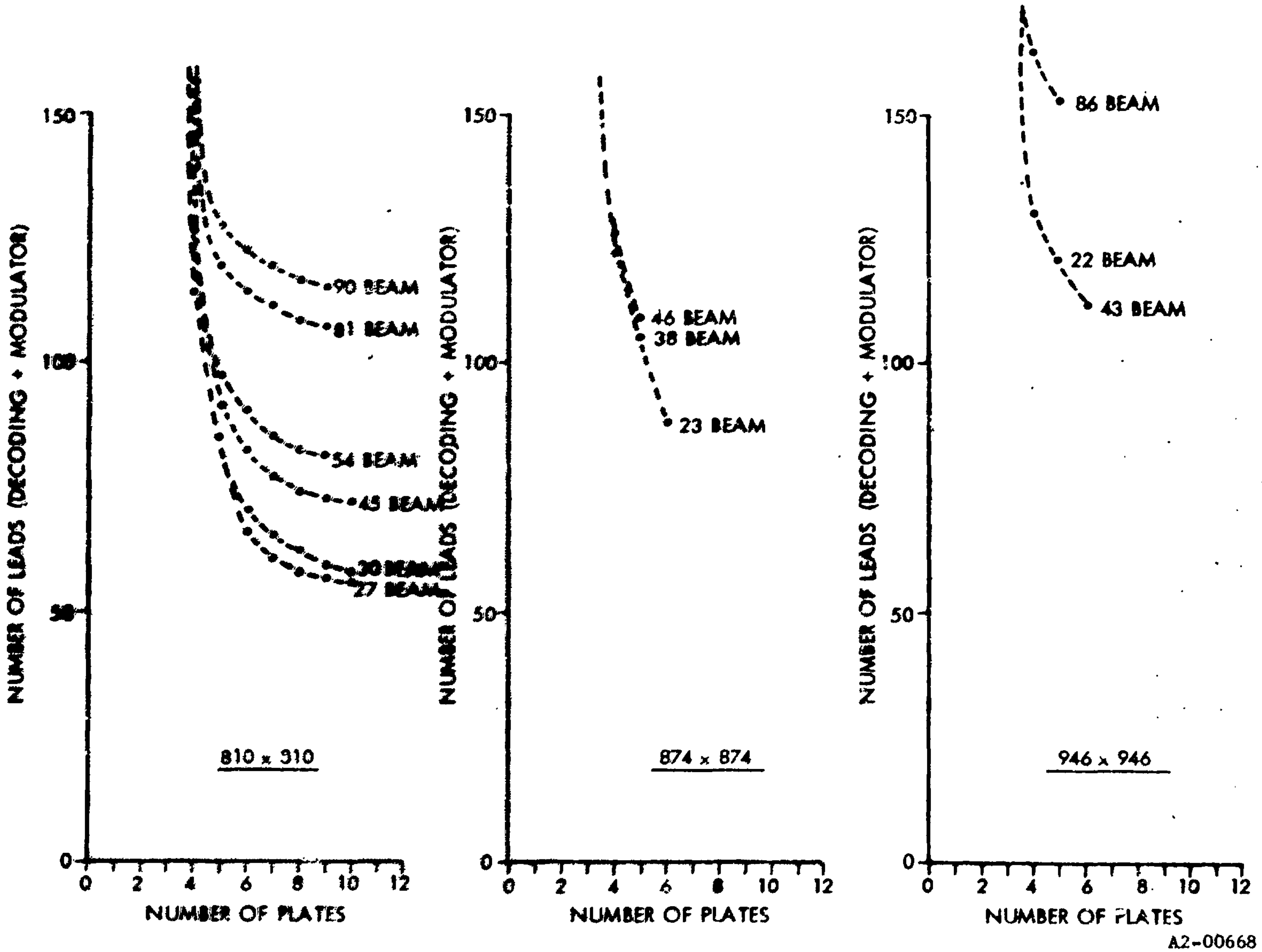


FIGURE 56 NUMBER OF CONDUCTOR LEADS REQUIRED FOR VARIOUS DIGISPLAY CONFIGURATIONS

TABLE 37

810 X 810 VDS DIRECT-VIEW STORAGE DIGISPLAY

CONFIGURATION	NO. BEAMS	NO. PLATES[1]	NO. LEADS[1]	CONTRAST RATIO[2]	LEAD CAPACITANCE (PF) V1	V2	V3	V4	H1	MOD	INPUT CURRENT DENSITY FOR 1100 FT-L[3]	FOR 2200 FT-L[3]	TOTAL INPUT POWER[4] FOR 1100 FT-L[3]	FOR 2200 FT-L[3]	REMARKS
27·30X27·(30)	30	4	114	124:1	900	2000	--	--	900	2000	3.7 MA/CM^2	7.9 MA/CM^2	220 Watts	315 Watts	Symmetric Design
27·30X18·(45)	45	4	120	140:1	900	2000	--	--	1350	1325	3.7	7.9	220	315	
27·30X15·(54)	54	4	126	146:1	900	2000	--	--	1600	1100	3.7	7.9	225	320	
27·30X10·(81)	81	4	148	157:1	900	2000	--	--	2400	750	3.7	7.9	230	325	
9·9·10X27·(30)	30	5	85	197:1	2675	2875	6000	--	900	2000	4.2	8.75	220	315	Least Number of Leads
9·9·10X18·(45)	45	5	91	239:1	2675	2875	6000	--	1350	1325	4.2	8.75	220	315	
9·9·10X15·(54)	54	5	97	257:1	2675	2875	6000	--	1600	1100	4.2	8.75	225	320	
9·9·10X10·(81)	81	5	119	295:1	2675	2875	6000	--	2400	750	4.2	8.75	230	325	Highest Contrast Ratio

1. DECODING AND MODULATOR PLATES ONLY
2. INHERENT CONTRAST RATIO WITH GAIN/CUTOFF = 10,000:1
3. WITH P44 PHOSPHOR @ 10 KV
4. WITH 1 OUT OF 8 SEGMENTED FLOOD GUN

TABLE 38

874 X 874 VDS DIRECT-VIEW STORAGE DIGISPLAY

CONFIGURATION	NO. BEAMS	NO. PLATES[1]	NO. LEADS[1]	CONTRAST RATIO[2]	LEAD CAPACITANCE (PF)						INPUT CURRENT DENSITY		TOTAL INPUT POWER[4]		REMARKS
					V1	V2	V3	V4	H1	MOD	FOR 1100 FT-L[3]	FOR 2200 FT-L[3]	FOR 1100 FT-L[3]	FOR 2200 FT-L[3]	
23·38X23·(38)	38	4	122	124:1	1250	1850	--	--	1250	1850	3.75 MA/CM^2	7.9 MA/CM^2	250 Watts	365 Watts	Symmetric Design
23·38X19·(46)	46	4	126	131:1	1250	1850	--	--	1500	1525	3.75	7.9	250	365	
19·46X19·(46)	46	4	130	124:1	1500	1525	--	--	1500	1525	3.75	7.9	250	365	Symmetric Design; Balanced Capacitance

1. DECODING AND MODULATOR PLATES ONLY
2. INHERENT CONTRAST RATIO WITH GAIN/CUTOFF = 10,000:1
3. WITH P44 PHOSPHOR @ 10 KV
4. WITH 1 OUT OF 8 SEGMENTED FLOOD GUN

TABLE 39

946 X 946 VDS DIRECT-VIEW STORAGE DIGISPLAY

CONFIGURATION	NO. BEAMS	NO. PLATES[1]	NO. LEADS[1]	CONTRAST RATIO[2]	LEAD CAPACITANCE (PF) V1	V2	V3	V4	H1	MOD	INPUT CURRENT DENSITY FOR 1100 FT-L[3]	FOR 2200 FT-L[3]	TOTAL INPUT POWER[4] FOR 1100 FT-L[3]	FOR 2200 FT-L[3]	REMARKS
43·22X43·(22)	22	4	130	96:1	800	3725	--	--	800	3725	3.75 MA/CM^2	7.9 MA/CM^2	295 Watts	425 Watts	Symmetric Design; Least Number of Leads
22·43X22·(43)	43	4	130	120:1	1500	1900	--	--	1500	1900	3.75	7.9	295	425	Symmetric Design; Least Number of Leads
22·43X11·(86)	86	4	162	138:1	1500	1900	-	--	3000	950	3.75	7.9	305	435	Highest Contrast Ratio
11·86X11·(86)	86	4	194	96:1	3000	950	--	--	3000	950	3.75	7.9	315	440	Symmetric Design

1. DECODING AND MODULATOR PLATES ONLY
2. INHERENT CONTRAST RATIO WITH GAIN/CUTOFF = 10,000:1
3. WITH P44 PHOSPHOR @ 10 KV
4. WITH 1 OUT OF 8 SEGMENTED FLOOD GUN

The computer output parameters listed for each configuration are the inherent contrast ratio, the lead capacitance, the required input current density, and the required input power for both 1100 and 2200 foot-Lambert operation. Note that the contrast ratios are given for a decoding plate gain-to-cutoff ratio of 10,000 to 1, which is quite commonly achieved with DIGISPLAY devices. The relationship between contrast ratio and the gain-to-cutoff ratio is illustrated in Figure 57 for typical situations. Note that for the higher values which are of particular interest to us there is nearly a linear dependence of contrast ratio on gain-to-cutoff ratio.

The inherent contrast ratios of all configurations analyzed are quite high ranging from a low of 95:1 to a high of 295:1. Since even the 95:1 contrast ratio permits the display of up to fourteen shades of gray (where the differential between shades is defined as a $\sqrt{2}$ change in brightness) in a low ambient environment, every one of the configurations studied would be suitable for the VDS on this basis at least. Note, however, that those configurations with more decoding plates and more scanning beams exhibit the higher inherent contrast ratios. This is illustrated in Figure 58 where the contrast ratio (at a gain-to-cutoff ratio of 10,000:1) is plotted as a function of the number of conductor leads for all of the 810x810 configurations studied. Configurations with fewer leads and higher contrast ratios are obviously preferred.

The lead capacitance of the various configurations studied was found to vary from about 750 to 6,000 picofarads, increasing with both format size and with the number of decoding plates. A graphical illustration of the lead capacitance of each of the fifteen configurations is given in Figure 59 The numbers to the right of each dot in the figure indicate the number of leads having this capacitance. The letter "M" following a number indicates that at least some of these leads are modulator leads. A small dot indicates that only one plate exhibits this capacitance; a large dot, two.

Note that all of the 874x874 configurations are quite attractive because of their balanced capacitance. This is especially true of the 19·46 x 19·(46) configuration which exhibits virtually the same lead capacitance for every plate. Hence this configuration could be operated in a random access mode with virtually the same performance experienced with the linear raster mode.

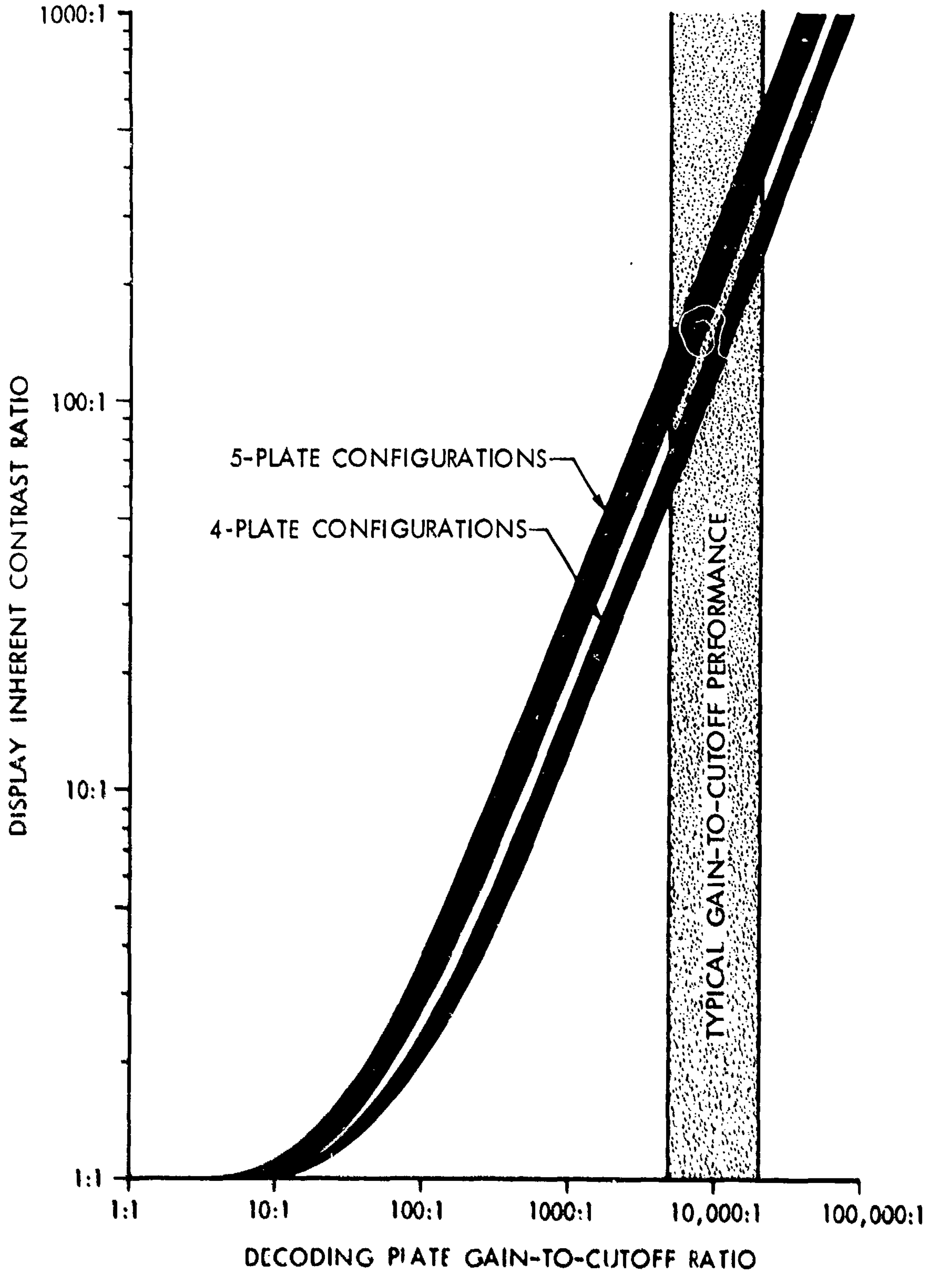


FIGURE 57 INHERENT CONTRAST RATIO OF DIGISPLAY DEVICES

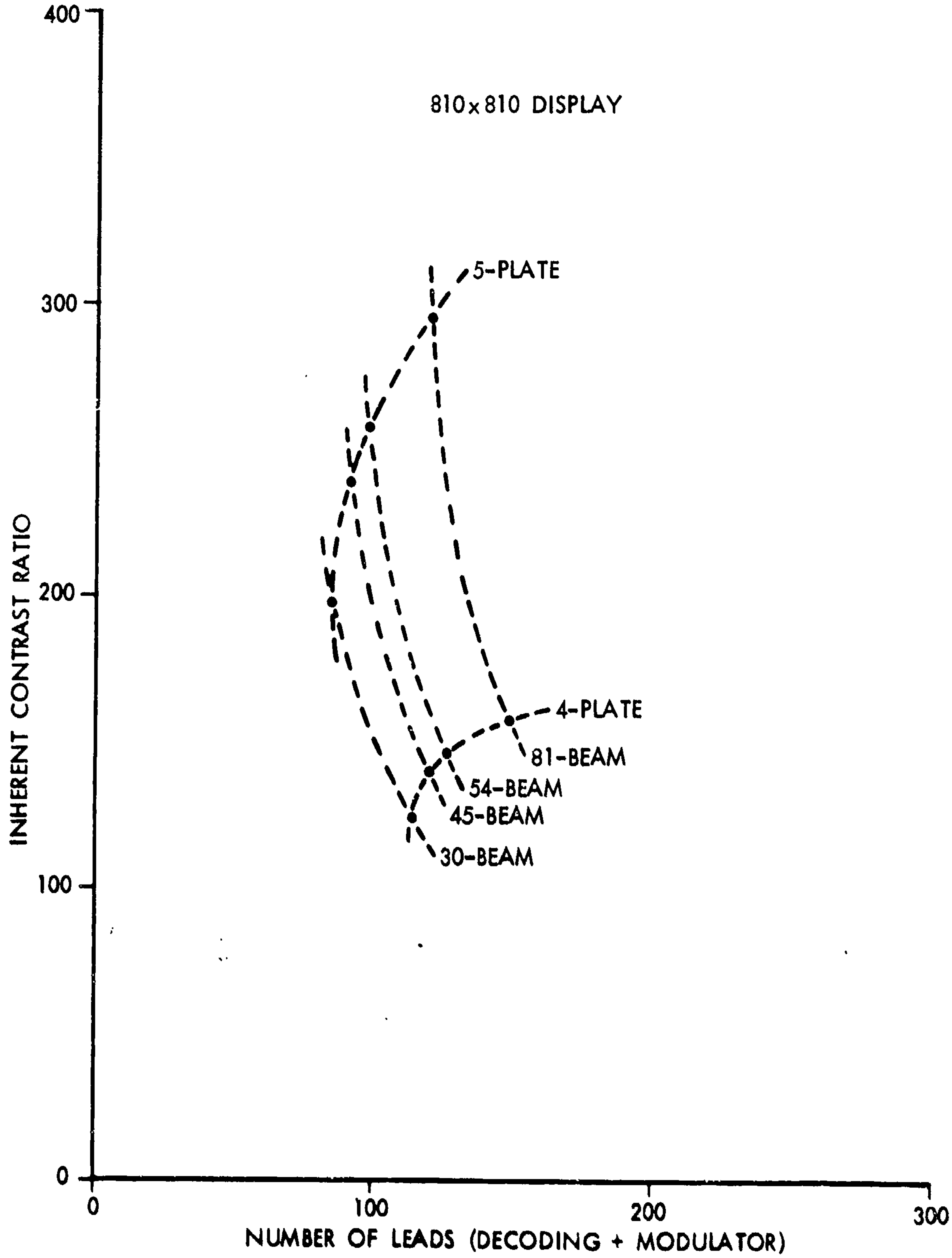


FIGURE 58 RELATIONSHIP BETWEEN INHERENT CONTRAST RATIO AND NUMBER OF CONDUCTOR LEADS FOR VARIOUS DESIGNS

A2-00665

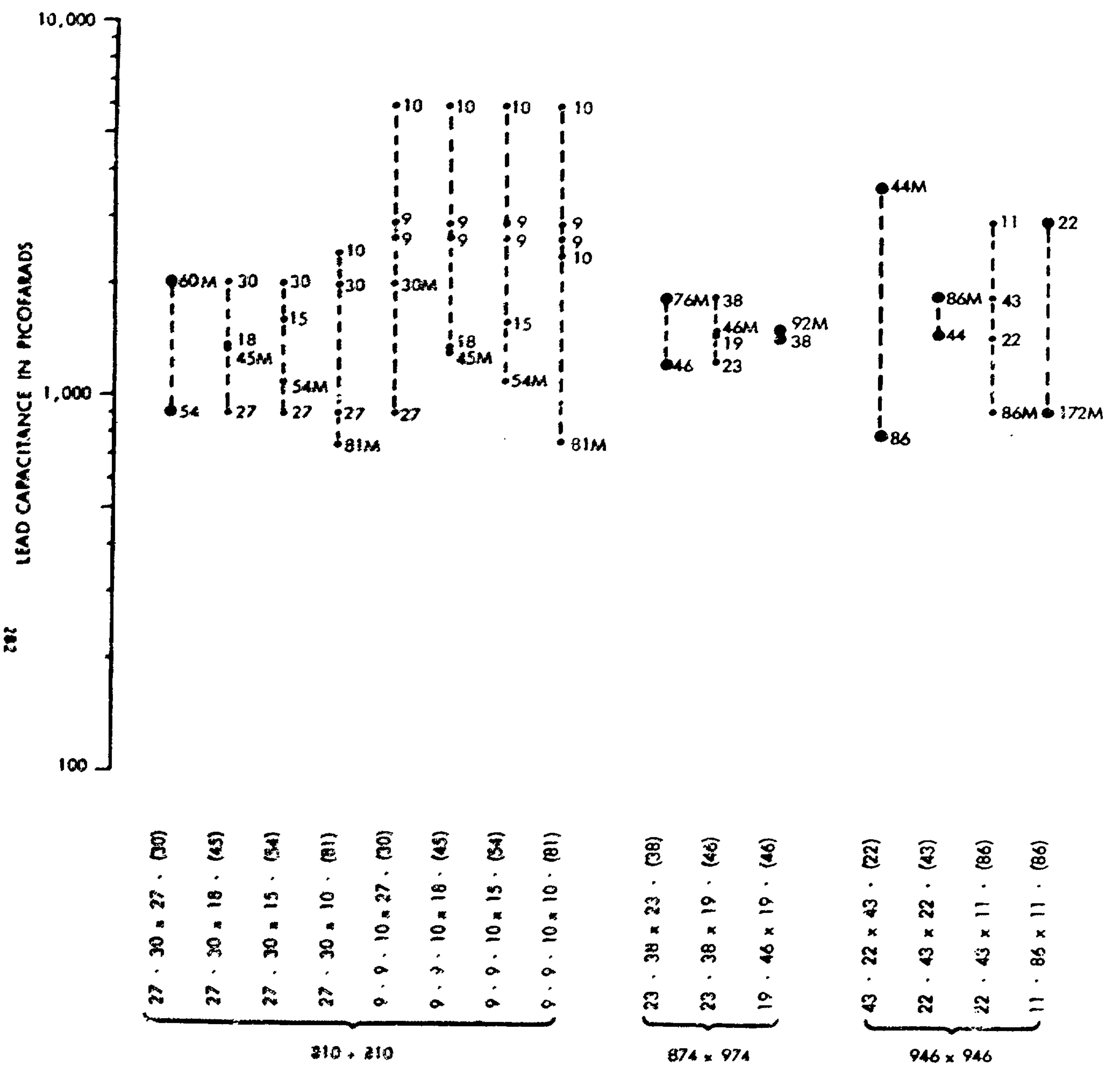


FIGURE 5[illegible] LEAD CAPACITANCE OF VARIOUS DIGISPLAY CONFIGURATIONS A2-00671

Conversely, the lead capacitance of the five-plate 810x810 configurations are very unbalanced; however, this unbalance is of only minor concern with regard to the VDS application because those leads which exhibit high capacitance are switched very infrequently when a raster scan is desired.

The minimum input current density required to adequately charge the storage mesh is illustrated in Figure 60 as a function of the display size and the number of multiple write beams. Note that a display having thirty or less write beams requires quite high input current densities especially for the larger display formats. Little is gained, however, in having many more than 40 write beams since the small savings in the input current requirement is more than offset by the increase in the number of modulator circuits required. Hence, 40 to 50 write beams seems to be ideal.

An engineering estimate of the total display system input power as a function of the display's screen brightness is given in Figure 61 . As might be expected, the input power increases as the square of the display size (linear with the display area). Note, however, that the input power requirement can be reduced significantly by operating at a higher phosphor excitation potential (e.g., at 14 or 18.5 kilovolts as shown in the figure) since the input current requirement can be greatly reduced. The input current cannot be reduced below that required to charge the storage mesh (see Figure 60), however, and hence there is a limit to the extent with which input current can be traded for phosphor potential. This limit can be relaxed, nevertheless, by designing the display with a greater number of multiple scanning write beams. For example, an input current density of only 2 ma/cm^2 would be sufficient to provide 1100 foot-Lambert operation with a 946x946 display but only if the phosphor potential were raised to 18.5 kilovolts and the number of write beams was in excess of sixty.

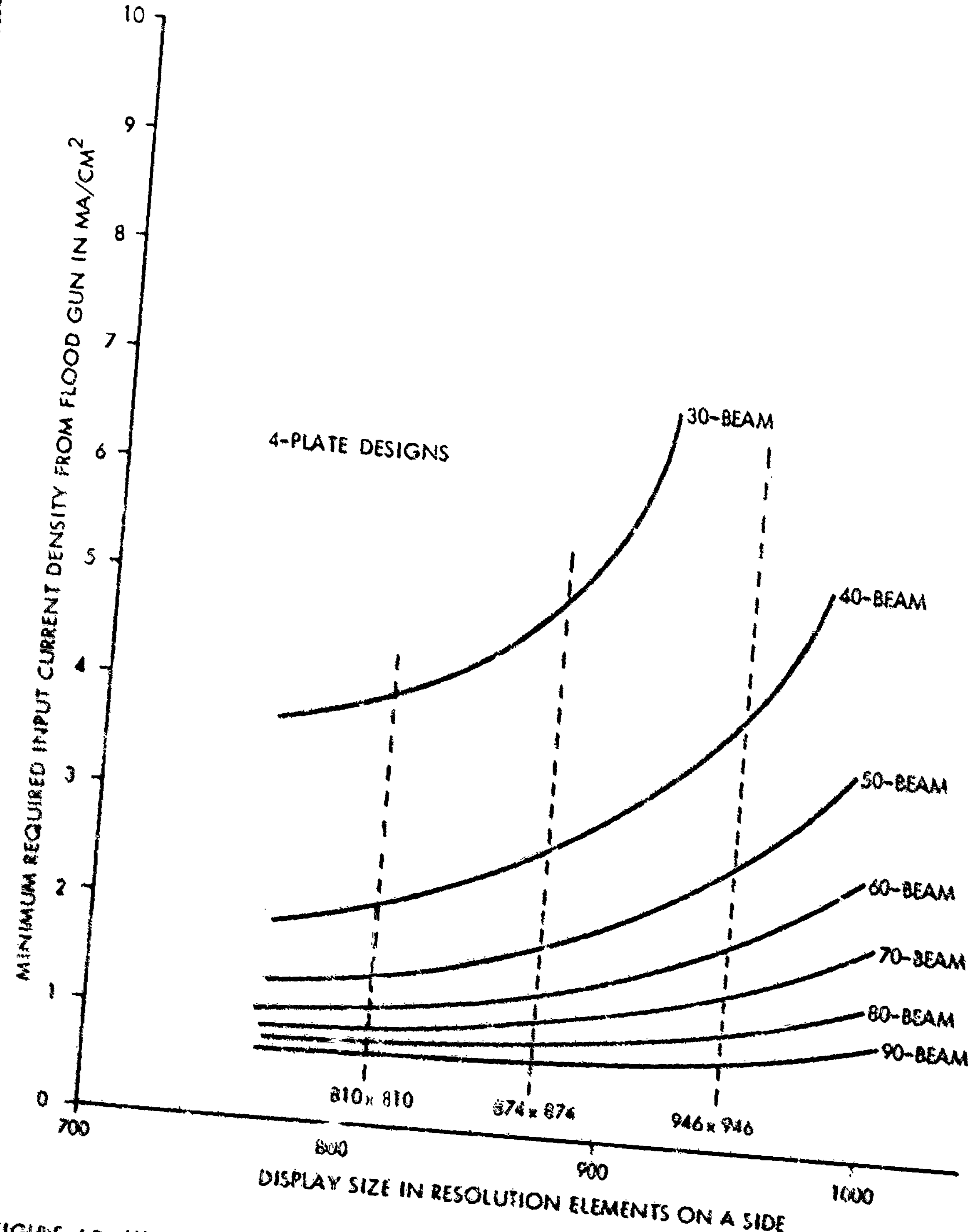


FIGURE 60 MINIMUM REQUIRED FLOOD GUN CURRENT DENSITY VS DISPLAY SIZE

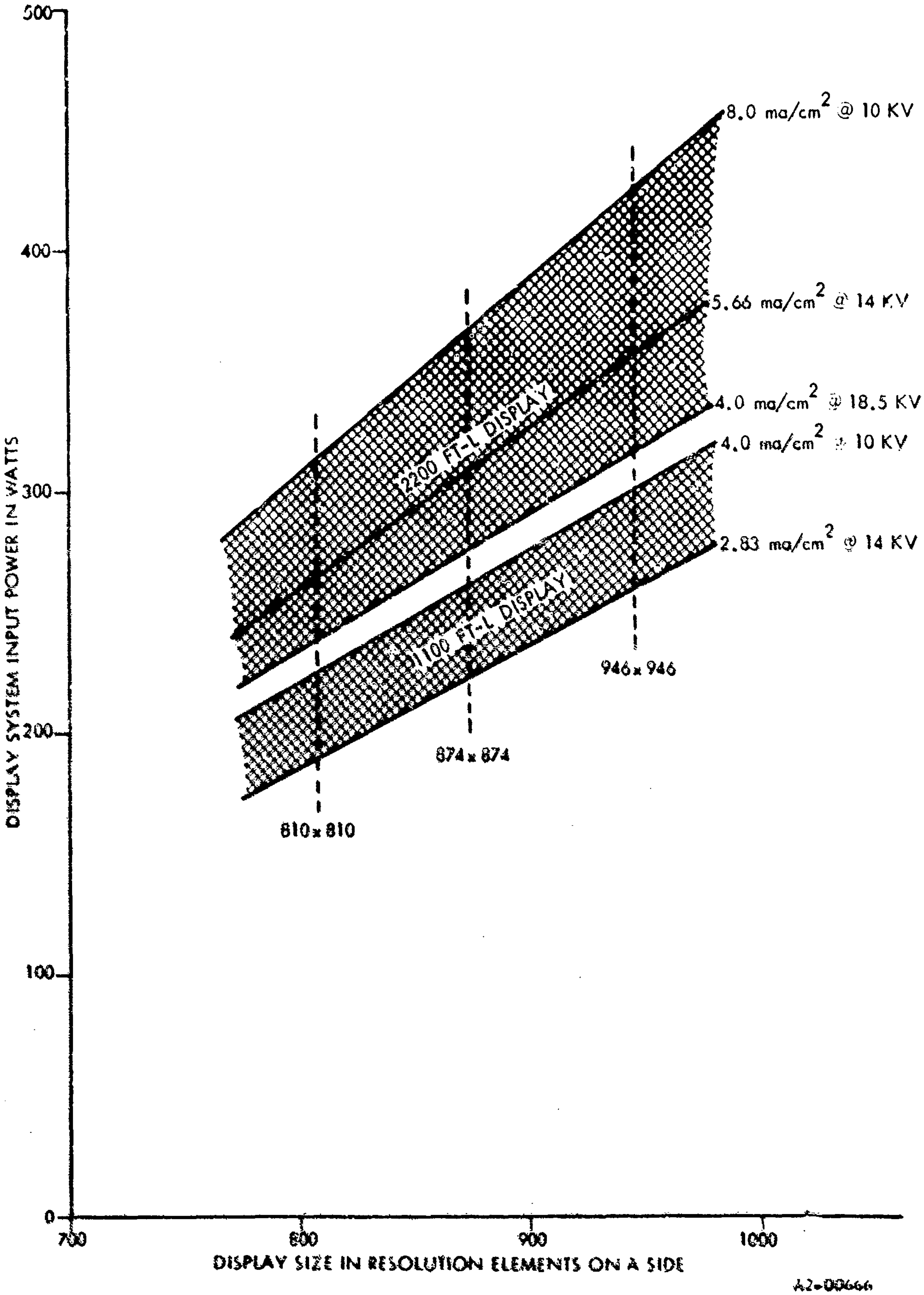


FIGURE 61 DISPLAY SYSTEM INPUT POWER VS DISPLAY SIZE

10.0 COST EFFECTIVENESS STUDY

This section will discuss the tradeoff considerations between the VDS design characteristics, performance, and cost considerations. A cost effectiveness analysis was conducted to determine the optimum design specifications from the alternate design approaches available, using 875, 945, and 1023 TV line scanning standards with eight or ten shades of gray imaging capability, for a 1985 non-CRT VDS.

10.1 OPTIMIZATION CRITERIA

The principal difficulty inherent in developing optimization criteria is not in defining the criterion, there are many available, but in choosing those which best represent the program objectives and are at the most appropriate level of detail. A useful systems level criterion, which may be employed, is that of system cost effectiveness. A generalized form of this criterion is:

$$\text{Cost Effectiveness (C.E.)} = \frac{(P)(A)}{C}$$

where P = Some measure of system performance

A = The availability of this performance when it is needed

C = Total cost which includes development, procurement and operating costs

A practical approach to the choice of an optimum system is to define, on a weighted criteria basis, the important system performance parameters and design characteristics and to compare the alternate designs on that basis. During the second part of the VDS study, representatives of NADC assigned a series of 24 weighted evaluation criteria to the most important system performance parameters and design characteristics to insure that the correct emphasis was given to the system parameters considered to be most important by the Navy. Seven of these weighting factors were used in the cost effectiveness study to compare the differences in performance between the alternate candidate systems under consideration. Only those parameters that are expected to provide different performance levels or design characteristics for the systems under consideration were considered. The system performance was calculated for the 875, 945, and 1023 TV line scanning standards and a screen brightness of 1100 foot-Lamberts, which can provide eight shades of gray in a 10,000 ft-Lambert environment, from the following expression.

$$\text{Cost Effectiveness (C.E.)} = \frac{(P)(A)}{C}$$

$$\text{Performance (P)} = \sum_{i=1}^{i=7} \frac{W_1}{B_1} + \frac{W_2}{B_2} + \frac{W_3}{B_3} + \frac{W_4}{B_4} + \frac{W_5}{B_5} + \frac{W_6}{B_6} + \frac{W_7}{B_7}$$

where W_1 = Resolution = 5 points

W_2 = Spot Size = 3 points

W_3 = Contrast = 8 points (0.15) = 2 points

W_4 = Screen Size = 4 points

W_5 = Volume = 4 points

W_6 = Weight = 3 points

W_7 = Power = 3 points

$B_{1 \text{ through } 7}$ = Normalized Performance Values

(A) = System Availability (MTBF)

C = System Cost

Note that each of the quantitative descriptions of the performance factors listed is such that the performance improves as the numbers decrease. Thus, all the B parameters are shown in the denominator. The weighting factor for system contrast was multiplied by a factor of (0.15), corresponding to the percentage of reduced light periods (dawn and dusk) during a 24-hour operational period. During full sunlight conditions all three TV scanning standards for a vidicon sensor system have an adequate signal-to-noise ratio and contrast to provide ten shades of gray scale. It is only during reduced lighting conditions that the contrast and gray scale capability of the systems is diminished.

10.2 CANDIDATE SYSTEMS RATINGS

The nine candidate VDS systems are listed in table 40. They utilize eight shades of gray scale, 875, 945, and 1023 TV line scanning standards with dot densities of 80, 90, and 100 dots per inch and screen sizes varying from 8 to 12 inches square corresponding to the scanning standard and dot density. The diagnostic simulation test results were used to determine the relative

TABLE 40. CANDIDATE SYSTEMS FOR VDS APPLICATION

SCANNING STANDARDS	RESOLUTION	SIZE
875 LINES	80 DOTS/IN	(10.1 IN)
	90 DOTS/IN	(9.0 IN)
	100 DOTS/IN	(8.09 IN)
945 LINES	80 DOTS/IN	(10.9 IN)
	90 DOTS/IN	(9.72 IN)
	100 DOTS/IN	(8.74 IN)
1023 LINES	80 DOTS/IN	(11.8 IN)
	90 DOTS/IN	(10.5 IN)
	100 DOTS/IN	(9.45 IN)

resolution performance of the candidate systems as shown in table 41, and a comparison of the key system parameters was prepared (see table 42) for three complete vertical display systems including the display, scan converter with interface electronics and computer.

Table 43 contains a complete breakdown of the points earned for each of the seven performance and design characteristics and for system availability and cost for the nine candidate systems. The 875 line scanning standard with the largest screen size (10 inches square) and with a dot density of 81 dots per inch scored the highest number of points and is, therefore, considered to be the most cost effective system. The relative cost effectiveness scores for all the systems are shown in table 44. All of the 875 line systems earned higher scores by approximately 40 percent than the 945 line systems, and all the 945-line systems earned approximately 20 percent higher scores than the 1023-line systems. Within each group the systems scores increased as the screen size increased. That is, the system with the largest screen size scored the highest number of points. The reasons for the lower scanning standards scoring the higher marks is basically due to the lower complexity of these systems, which results in increased reliability (MTBF) and improved system contrast with lower volume, weight, power, and cost figures.

The next cost effectiveness comparison study was to determine if the 875 TV scanning standard using 10 shades of gray with a four-bit scan converter was superior to the 875-line system with eight shades of gray scale with a three-bit scan converter. Table 45 shows a comparison of the key parameters for an eight and ten shades of gray system using the 875 line scanning standards. The cost effectiveness of each system was determined from the following expression, which compares the key parameters which are different for the two systems.

$$\text{Cost Effectiveness (C.E.)} = \frac{(P)(A)}{C}$$

where

$$P = \sum_{i=1}^{i=4} \frac{W_1}{B_1} + \frac{W_2}{B_2} + \frac{W_3}{B_3} + \frac{W_4}{B_4}$$

TABLE 41. SYSTEM RESOLUTION PERFORMANCE

SCANNING STANDARD TV/LINES	RESOLUTION DOTS/IN	SCREEN SIZE INCHES	VERTICAL RESOLUTION L/P WIDTH	HORIZONTAL RESOLUTION L/P WIDTH	AVERAGE RESOLUTION L/P WIDTH	RELATIVE PERFORMANCE
875	80	10.1	263	285	274	0.879
875	90	9.0	223	252	239	0.767
875	100	8.1	185	230	208	0.667
945	80	10.9	280	306	293	0.939
945	90	9.72	252	288	270	0.865
945	100	8.74	205	250	228	0.730
1023	80	11.8	297	327	312	1.00
1023	90	10.5	278	316	297	0.955
1023	100	9.45	235	280	258	0.826

TABLE 42. COMPARISON OF KEY PARAMETERS FOR 875, 945 AND 1023 DIGISPLAY SYSTEMS

	875 LINE SYSTEM				945 LINE SYSTEM				1023 LINE SYSTEM			
	DISPLAY	SCAN CONV.	COMP.	TOTAL	DISPLAY	SCAN CONV.	COMP.	TOTAL	DISPLAY	SCAN CONV.	COMP.	TOTAL
WRITING BEAMS	45	2.129×10^6 BITS	4000 WORDS	-	46	2.481×10^6 BITS	4000 WORDS	-	43	2.903×10^6 BITS	4000 WORDS	-
SWITCHING LEADS	91	-	-	91	126	-	-	126	130	-	-	130
S/N RATIO	30	-	-	30	27	-	-	27	20	-	-	20
VOLUME IN^3	1268	320	300	1888	1360	372	300	2032	1383	436	300	2119
WEIGHT POUNDS	45.6	10.7	10	66.3	49.3	12.4	10	71.7	51.7	14.5	10	76.2
POWER WATTS	190	107	27	324	227	124	27	378	289	145	27	461
MTBF	7100	13,000	8000	2920	5120	11,150	8000	2450	5000	9550	8000	2350
COST \$1000	25	12.8	10	47.8	30	14.9	10	54.9	35	17.5	10	62.5

TABLE 43 SYSTEMS COST EFFECTIVENESS PARAMETERS

SCAN STD.	RESOLUTION 5 PTS.	SPOT SIZE 3 PTS.	CONTRAST 8 PTS. (0.15) = 2 PTS.	SCREEN SIZE 4 PTS.	VOLUME 4 PTS.	WEIGHT 3 PTS.	POWER 3 PTS.	AVAIL. MTBF 12 PTS.	SYSTEM COST	TOTAL POINTS
875	4.39	2.4	2.0	2.94	4.0	3.0	3.0	12.0	1.0	261
875	3.83	2.7	2.0	2.94	4.0	3.0	3.0	12.0	1.0	259
875	3.33	3.0	2.0	2.94	4.0	3.0	3.0	12.0	1.0	256
945	4.70	2.4	1.38	3.42	3.73	2.77	2.59	10.1	1.15	184
945	4.32	2.7	1.38	3.42	3.73	2.77	2.59	10.1	1.15	183
945	3.65	3.0	1.38	3.42	3.73	2.77	2.59	10.1	1.15	180
1023	5.00	2.4	1.02	2.94	3.56	2.60	2.11	9.69	1.31	153
1023	4.77	2.7	1.02	2.94	3.56	2.60	2.11	9.69	1.31	153
1023	4.13	3.0	1.02	2.94	3.56	2.60	2.11	9.69	1.31	151

TABLE 44 COST EFFECTIVENESS RATINGS OF 875, 945 AND 1023 LINE SYSTEMS

1100 FOOT-LAMBERTS SCREEN BRIGHTNESS 8 SHADES OF GRAY

SCANNING STANDARDS	RESOLUTION	SIZE		POINTS	RELATIVE (CE)
875 LINES	80 DOTS/IN	(10.1 IN)	=	261	1.000
	90 DOTS/IN	(9.0 IN)	=	259	0.988
	100 DOTS/IN	(8.09 IN)	=	256	0.977
945 LINES	80 DOTS/IN	(10.9 IN)	=	184	0.710
	90 DOTS/IN	(9.72 IN)	=	183	0.700
	100 DOTS/IN	(8.74 IN)	=	179.5	0.690
1023 LINES	80 DOTS/IN	(11.8 IN)	=	153	0.590
	90 DOTS/IN	(10.5 IN)	=	153	0.590
	100 DOTS/IN	9.45 IN)	=	151	0.580

TABLE 45

DIGISPLAY VDS (875 TV LINE SCANNING STANDARD)
COMPARISON OF 8 VERSUS 10 SHADES OF GRAY CAPABILITY

	8 SHADES OF GRAY				10 SHADES OF GRAY			
	DISPLAY	SCAN CONVERTER	COMPUTER	TOTALS	DISPLAY	SCAN CONVERTER	COMPUTER	TOTALS
DISPLAY BRIGHTNESS (FOOT-LAMBERTS)	1100 F-L	2.129×10^6 BITS	4000 WORDS	-	2200 F-L	2.784×10^6 BITS	4000 WORDS	-
PACKAGE VOLUME (INCHES)	1268	320	300	1888	1340	418	300	$2058^{(1.09)}$
PACKAGE WEIGHT (POUNDS)	45.6	10.7	10	663	49.8	13.9	10	$73.7^{(1.1)}$
POWER CONSUMPTION (WATTS)	190	107	27	324	239	139	27	$405^{(1.25)}$
MTBF (HOURS)	7100	13,000	8000	2920	7100	10,000	8000	$2730^{(1.07)}$
COST (DOLLARS)	25	12.8	10	47.8	26	16.75	10	$52.75^{(1.1)}$

W_1 = Contrast = 8 points

W_2 = Volume = 4 points

W_3 = Weight = 3 points

W_4 = Power = 3 points

A = System Availability (MTBF) = 12 points

C = System Cost

$$\text{8 shades of gray system} = \left[\frac{8}{1.53} + \frac{4}{1} + \frac{3}{1} + \frac{3}{1}\right]\frac{12}{1} = 192 \text{ points} = 1.00$$

$$\text{10 shades of gray system} = \left[\frac{8}{1} + \frac{4}{1.09} + \frac{3}{1.1} + \frac{3}{1.25}\right]\frac{12}{1.09} = 187 \text{ points} = 0.87$$

10.3 COST EFFECTIVENESS STUDY RESULTS

The following general conclusions can be drawn from the cost effectiveness tradeoff studies.

1. Video systems with larger screen sizes (lower dot densities within the range of 80 to 100 dots per inch) are more cost effective than those systems with smaller screen sizes for the same scanning standards.

2. Systems using lower scanning standards are more cost effective than those using higher scanning standards (within the range of 875 to 1023 TV lines).

3. Systems using eight shades of gray are more cost effective than those using ten shades of gray for the same scanning standards.

The cost effectiveness comparison indicates that the 875-line system using eight shades of gray is approximately 13 percent more cost effective than the ten-shade-of-gray system. The reason for the higher score obtained by the eight shades of gray system is due to lower system complexity which leads to improved reliability (MTBF) and lower volume, weight and power. It is, therefore, the conclusion of this study that the 875 TV line scanning standard with a three-bit scan converter, providing eight shades of gray scale and a screen brightness of 1100 foot-Lamberts, is the most cost effective system (provides the highest performance per unit cost of all systems considered) for the VDS application. This system will be used as the baseline for a preliminary design analysis which is given in the next section.

11.0 DIGISPLAY - DESIGN CONCEPT FOR A 810x810 RESOLUTION ELEMENT VDS DISPLAY SYSTEM

The following sections provide a brief description of the display device and the design approaches to problems which will be encountered in mechanizing the display system. Some of these concepts have already been demonstrated in laboratory development hardwar (though on devices with fewer resolution elements (512x512)) while others will require additional design and development.

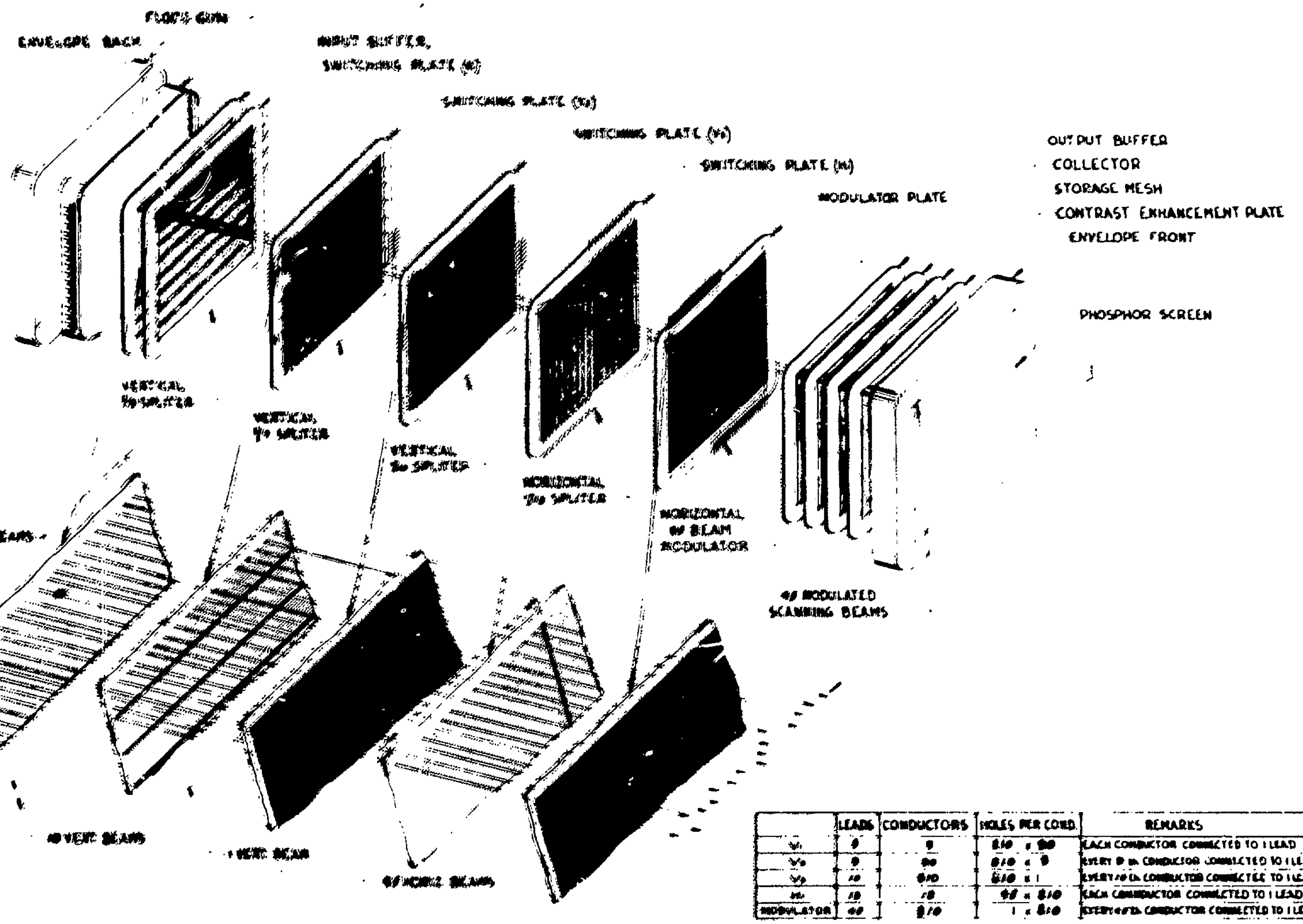
The electronic design assumes an 810x810 resolution element display with a resolution of 81 holes per inch, 45 simultaneous writing beams and 5 switched control plates. A screen brightness of 1100 foot-Lamberts was also assumed with an accelerating potential of 14.75 KV. This brightness level can provide 8 shades of gray scale ($\sqrt{2}$ steps) in a 10,000 foot-Lamberts ambient environment by use of a narrow bandpass filter matched to the relatively narrow output spectral lines of the phosphor.

11.1 DIGISPLAY DEVICE DESCRIPTION

The DIGISPLAY device for the 810x810 display consists of an area cathode electron source, a series of switching and fixed potential plates which control the electron beams, a storage target and a phosphor. See figure 62.

The area electron source emits electrons over an extended area slightly larger in size than the active area of the switching plates. Two additional electrodes called the cup and input buffer are used to focus the electrons and accelerate them toward the switching plates which control electron flow. The electron current density at the input buffer control plate is 2.83 mA/cm^2. The active display area is 10.0x10.0 inches or 25.4x25.4 cm giving an area of 645 cm^2. The current output of the electron source over the active display area is therefore 2.83 mA/cm^2 x 645 cm^2 = 1.82 A.

FIGURE 62 EXPLODED VIEW OF MULTIBEAM VDS DIGISPLAY
(810 X 810 ELEMENTS - 45 SCANNING BEAMS)



	LEADS	CONDUCTORS	HOLES PER COND.	REMARKS
V_1	9	9	810 x 90	EACH CONDUCTOR CONNECTED TO 1 LEAD
V_2	9	90	810 x 9	EVERY 9th CONDUCTOR CONNECTED TO 1 LEAD
V_3	10	810	810 x 1	EVERY 10th CONDUCTOR CONNECTED TO 1 LEAD
H_1	18	18	45 x 810	EACH CONDUCTOR CONNECTED TO 1 LEAD
MODULATOR	45	810	1 x 810	EVERY 45th CONDUCTOR CONNECTED TO 1 LEAD

The five control plates (V1, V2, V3, H1 and modulator plates) are used to perform the scanning and modulation functions during the writing mode. In the FLOOD and ERASE modes these plates are all turned ON.

Additional plates are the output buffer and collector plates. They are used to focus the electrons which pass through the modulator plate onto the storage target in the WRITE mode. The collector plate is also used to collect electrons repelled by the storage target in the FLOOD and ERASE modes and secondary electrons from the storage target in the WRITE mode.

The next electrode is the storage mesh. The storage mesh is basically a high resolution metallic mesh upon which a special dielectric has been deposited. The dielectric is placed on the side facing the collector plate. It is upon this dielectric that charge is deposited and information retained.

The contrast enhancement plate follows the storage mesh assembly. It performs a dual purpose. First it is used to enhance the display contrast by acting as a blanking grid during the ERASE mode. Secondly, it refocuses the image which has been retained on the storage mesh and redefines the spot size.

The phosphor target and envelope assembly form the viewing surface and suitable vacuum environment within which the display operates. The aluminized phosphor is deposited on the viewing face of the envelope assembly and is placed in close proximity to the contrast enhancement plate.

11.1.1 Decoding

In the WRITE mode the address decoding and modulating functions are performed collectively by control plates V_1, V_2, V_3, H_1 and the modulator plate. See figure 62. The output of these five control plates is a set of 45 adjacent collinear beams. Signal information is imparted to the 45 beams by a 45 lead modulator plate. Decoding on the two axes is done independently. Three decoding plates (V_1, V_2, and V_3) are used to decode the vertical axis. Two plates decode the horizontal axis (H_1 and the modulator plate).

The V_1 plate divides the electron beams from the flood gun into nine horizontal segments each 90 resolution elements in height. In the WRITE mode one of these segments would be ON and eight would be biased OFF. Thus, the output from the V_1 plate is a matrix of electron beams, 810 resolution elements wide and 90 resolution elements high. The V_2 plate divides the output from the V_1 plate into 9 horizontal segments each 10 resolution elements high, thus its output is a matrix 810 resolution elements wide and 10 resolution elements high.

The V_3 control plate divides the output of the V_2 plate into ten horizontal strips each one resolution element high. The output of V_3 is a collinear array of 810 adjacent electron beams. This completes the vertical axis decoding. The H_1 control plate divides the output from V_3 into eighteen vertical segments. The output from H_1 is a collinear array of 45 adjacent electron beams. Each of the 45 beams is individually modulated and the resulting beams WRITE on the storage mesh.

11.1.2 Mechanical Design

The mechanical design features and ruggedization approach for the DIGISPLAY device are discussed in the following sections. Thermal design and electronics packaging approaches are also discussed.

DIGISPLAY Device Mechanical Design

Figure 62 is an exploded view of the DIGISPLAY for the VDS system. The ten specific component sections of the device are identified on the drawing. These sections are in order, the area electron gun, input buffer plate, the switching plate stack, modulator plate, output buffer plate, collector plate, storage mesh, contrast enhancement plate, phosphor target, and the envelope.

1) Electron Gun - The area electron gun emits an electron beam of virtually constant current density over the entire active area of the display device. The electron gun structure is constructed of stainless steel and consists of an array of thermionic electron emitters and one or more electrodes used to defocus the emitted electrons into a uniform large area beam. This beam serves as an input source to the switching plate stack which is the heart of the device. DIGISPLAY devices are presently operating with area electron guns that emit a beam with greater than 1 mA per square centimeter

current density over a 3.5x5.0 inch area. These devices operate with a ±10 percent variation in brightness over the display area. An improvement in flood gun output by a factor of 3 is required to obtain the current density and uniformity required for the VDS application.

2) Input Buffer Plate - The input buffer plate is used to isolate cathode voltages from the switching plate structure.

3) Switching Plate Stack - The electron gun provides a uniform source of electrons for the switching plate stack. This stack contains the control plates necessary to accomplish the scanning format. Each switching plate is a thin sheet of glass with holes photochemically etched through at each location where a display resolution element is required. The holes in the plates are lined with a thin film metallic coating, and electrodes (finger patterns) are arranged on the surfaces of the plates to connect the metal linings of the holes, or channels, into logical groups. The electrode patterns on each plate in the device are different. Although the stack is made of relatively thin glass plates, after fusing it becomes a very compact (approximately 0.1 inch thickness) and rugged assembly.

The plates are separated by glass spacers and sealed together so that the channels in all the plates are aligned. The basic operating principle of the device is that for a resolution element to be illuminated on the display, the channels corresponding to that resolution element on all the switching plates must be positively biased with respect to the area electron source. That is, a negative bias on a channel on any one plate is sufficient to prevent the corresponding resolution element from being illuminated.

4) Modulation Plate - This plate is structurally the same as the switching plates and is used to modulate the electron current level in the scanning beams and obtain gray scale in the video image. Present modulation design has successfully demonstrated $12(\sqrt{2})$ gray scale steps from the highlight level to black level.

5) Output Buffer Plate - This plate is identical to the switching plates except that it has continuous electroding over both plate surfaces instead of a decoding finger pattern. It is used at the output of the switching stack to isolate the switching plates from the field of the collector plate.

6) Collector Plate - This plate is identical to the output buffer plate. In the WRITE mode it is used to focus the electron beams onto the storage target and also to collect secondary electrons from the storage target. In the FLOOD and ERASE modes it collects electrons repelled by the storage target.

7) Storage Target - The storage target is a metal mesh coated on the electron input side with a dielectric material having good secondary electron emission (SEE) characteristics. Typically a SEE yield of unity is obtained at 40 volts and yields of 2-3 at several hundred volts of primary energy.

8) Contrast Enhancement Plate - This plate is similar to the output buffer and collector plates in that it has continuous electroding over both of its plate surfaces. It is located on the phosphor side of the storage target, and is used to prevent electrons from striking the phosphor screen when the storage target is being erased.

9) Phosphor Target - The portion of the electron beam allowed to pass through the switching stack at any time is accelerated to a phosphor target when the video image is formed. The phosphor target consists of a layer of P44 phosphor deposited on the inside of the envelope faceplate and covered by a thin aluminum layer. By operating this phosphor at a high voltage it emits light when bombarded by an electron beam.

10) Envelope - The purpose of the envelope is to enclose the components described above and maintain the vacuum integrity required for the operation of an electron beam. It also must provide a stable mounting platform

Thermal Considerations

Control of the thermal environment of the display package may be required to minimize package volume. The system can be designed with a cold plate as an integral part of the package. The cold plate can sink heat from the display device and from the electronics. Each electronics assembly can be packaged to interface with the cold plate by providing a thermal path to maintain a design temperature rise above the inlet coolant temperature. A

coolant temperature rise ΔT above inlet coolant temperature is expected to be 20 degrees C for a flow of 0.95 lb/minute for coolants such as Coolanol 25 or Flo-cool 180. This coolant flow rate is capable of removing a total of 190 watts of continuous heat input which is the total power dissipation of the 810x810 DIGISPLAY system. Typical aircraft liquid cooling systems are expected to maintain inlet temperatures in the range of +10 to +27 degrees C.

Ruggedization and MIL Qualifications

The DIGISPLAY inherently lends itself very well to ruggedization. The compactness and simple geometry of the envelope, the simple construction of the electron flood gun, and the fused switching stack, storage target, and contrast enhancement plate all contribute to the ease of ruggedizing this device.

Electronics Packaging

The display device will be housed in a frame behind the display front panel. The device will be suspended inside the housing by a layer of encapsulating material which will bond the device envelope to the panel and frame structure and will also sink heat from the device to the structure and cold plate. A drawing of the display device package is shown in figure 63.

The display device is shielded at the rear, top, bottom and sides by a magnetic shield which helps to protect the device from power system fields and also shields the connections to the device which are located around the periphery of the envelope. The high voltage (+14.75KV) lead to the phosphor will be located at one corner of the device and will be encapsulated.

11.2 VDS SYSTEM DESIGN

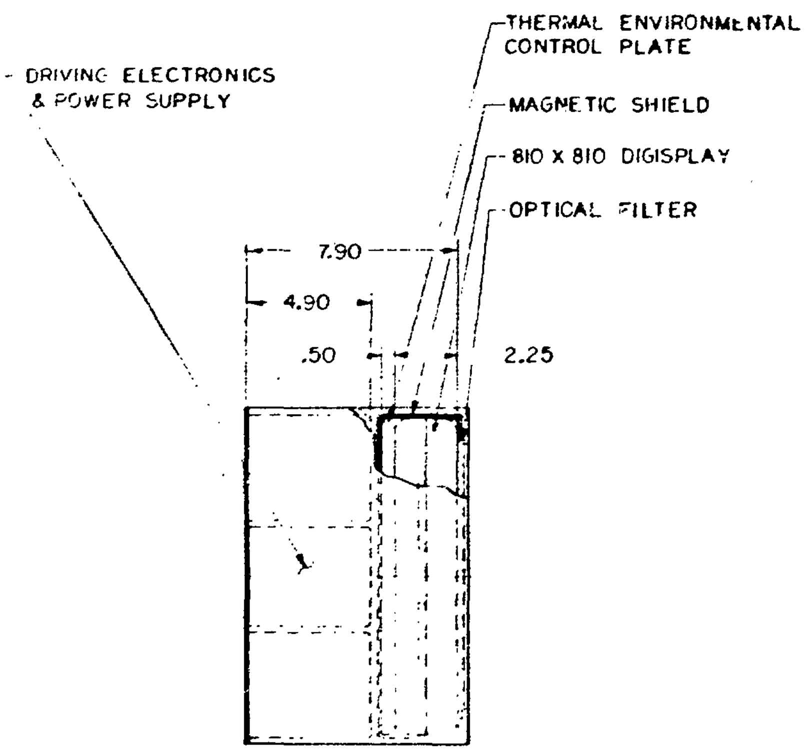
A block diagram of the overall VDS system is shown in figure 64. The major functional units shown on this diagram will be discussed in the following sections.

11.2.1 Display Scanning Standards

The TV raster scan format is in accordance with Electronic Industries Association Standard RS-343A (Electrical Performance Standards for High Resolution Monochrome Television Camera) for 875 line systems.

This format provides 809 active lines of display per frame made up from two interlaced fields of 404.5 lines each. The display writes on all 810 lines since the uppermost and lowest lines are "half-lines". The read address

	VOLUME	WEIGHT
DIGISPLAY	324 CU IN	12.7 LB
THERMAL CONTROL PLATE	80	6.0
ELECTRONICS & POWER SUPPLY	600	18.0
STRUCTURE CABLING & PACKING FRACTION	264	8.9
TOTAL	1268 CU IN	45.6 LB



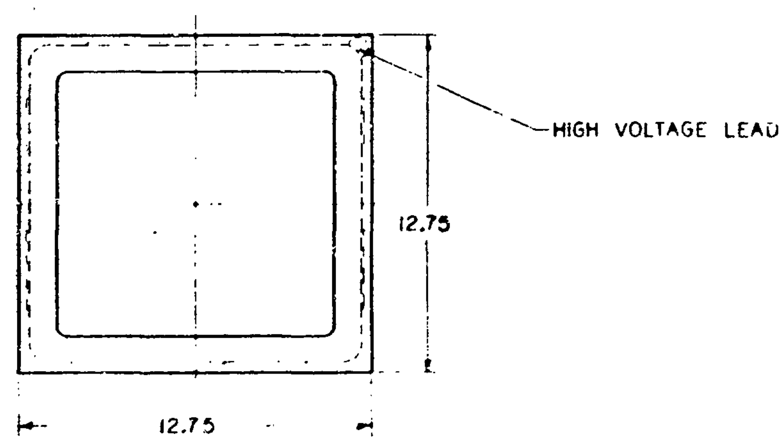


FIGURE 63 - 810X810 VDS DISPLAY - PACKAGING CONCEPT

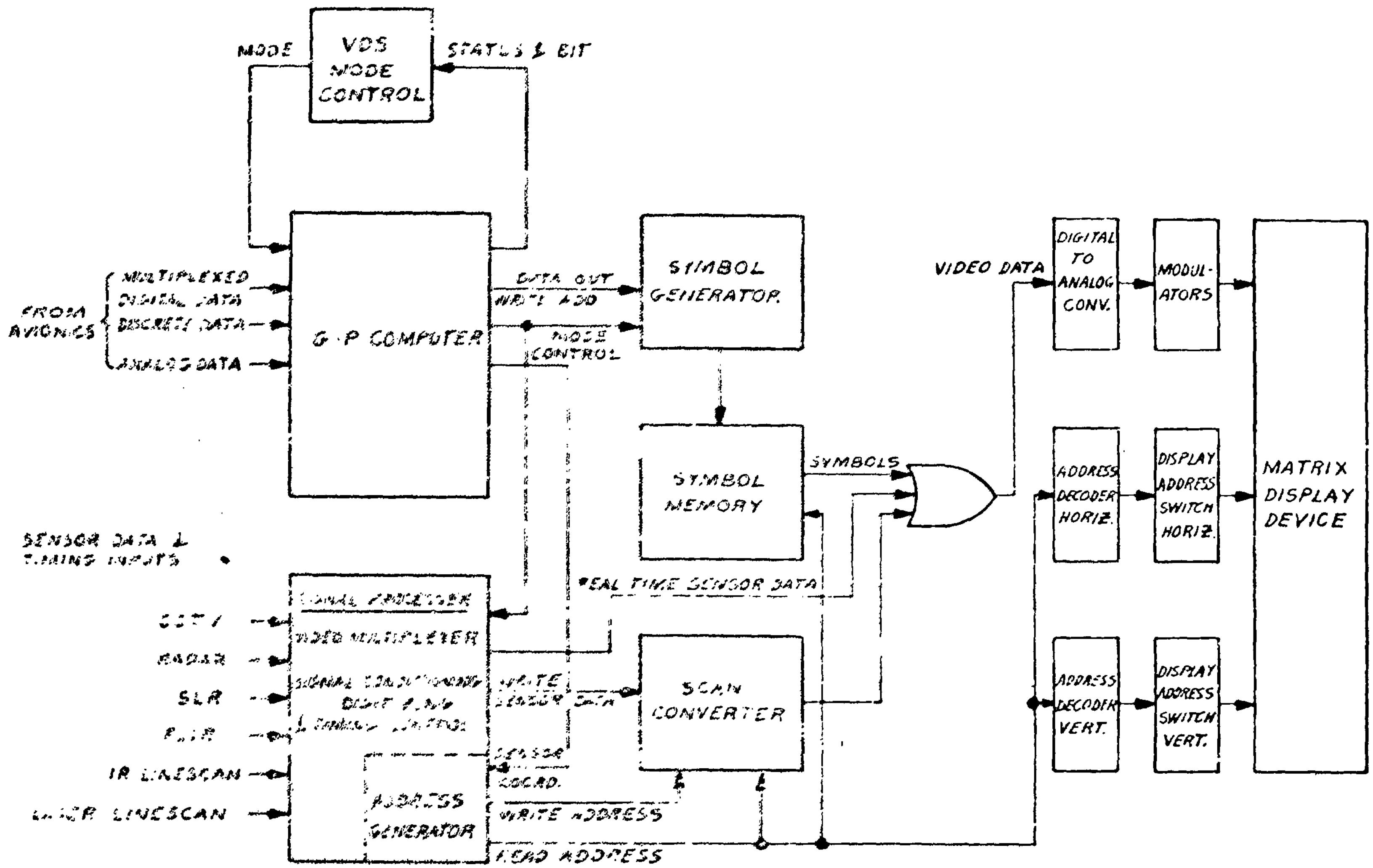


FIGURE 64 - VDS SYSTEM BLOCK DIAGRAM

generator of this video processor/scan converter can be used to derive the display system clock signal. The horizontal line period is 38.09 μsec and the active horizontal line time is 32.09 μsec (RS-343A). If the active horizontal line time contains 18 clock periods and the horizontal blanking time contains 4 clock periods the clock period will be $\frac{38.09\ \mu sec}{22} = 1.73\ \mu sec$ and the active line time will be 18x1.73 μsec = 31.14 μsec which is close to the 31.09 μsec shown in RS-343A.

The display system clock increments the horizontal address generator which drives the H_1 switching decoder. The vertical switching plate decoders are driven by the vertical address from the read address generator.

The display block diagram is shown in figure 65. Figure 66 shows the display waveforms which perform the scanning and modulation in the WRITE mode, readout in the FLOOD mode and selective erasure in the ERASE mode. The unblanking waveform is also shown. The basic display clock period of 1.73 μsec is divided into two parts: 0.45 μsec which is used to switch the horizontal decoding segments of plate H_1 and also to switch the D-A converter/modulator combinations to new data for the next writing period, and a writing period of 1.28 μsec.

The unblanking signal turns the beams ON only during the 1.28 μsec writing periods in the WRITE mode. In the FLOOD and ERASE modes the beams are also unblanked for the periods shown in the waveforms.

The modulator waveforms are shown stepped to illustrate the timing relationships with the other system waveforms.

The VC, VST and VCE waveforms are the voltages at the collector plate, storage target and contrast enhancement plate, respectively.

11.2.2 Signal Processor

The signal processor interfaces with the various sensors accepting signal data, timing data and in some cases sensor coordinate data. The signal processor conditions and digitizes the signal data and uses the coordinate

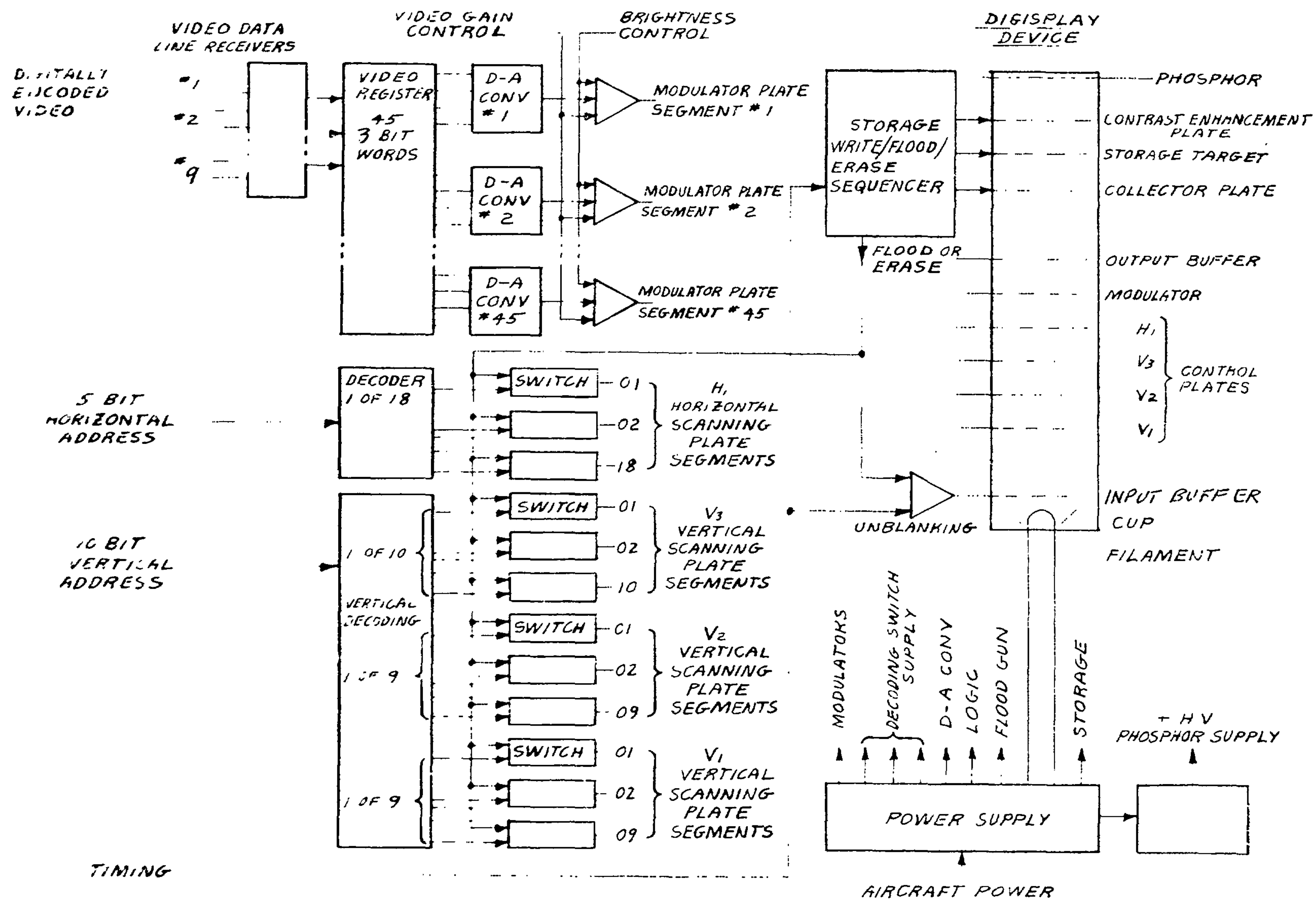


FIGURE 65 810x810 VDS DISPLAY BLOCK DIAGRAM

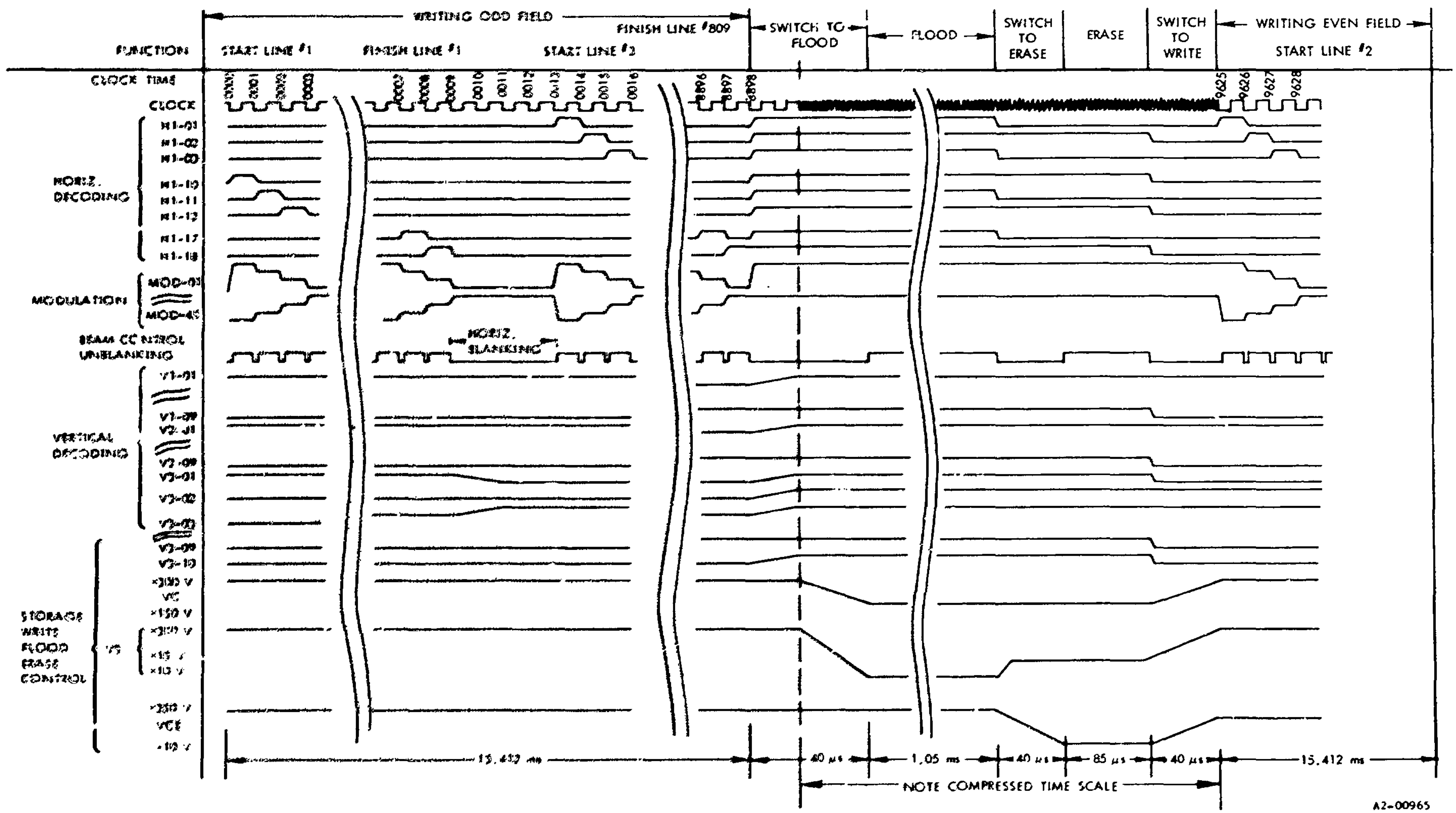


FIGURE 44 810 x 810 VDS DISPLAY WAVEFORMS

and timing data to generate appropriate addresses so that the sensor data may be written into the scan converter. The signal processor also provides digitized real-time data outputs from 875 line TV scan sources. The signal processor also generates the read addresses which provide the TV raster format for reading the scan converter and symbol memory.

The TV raster format can be the same for both real-time TV inputs and for other sensors which use the scan converter.

The signal processor conditions the sensor signals prior to encoding. This includes:

1) adjusting peak-to-peak signal amplitude to standard value for A-D converter
2) white peak clipping
3) gamma correction
4) DC restoration.

The conditioned video is then encoded by the A-D converter into a three-bit gray shade.

For TV raster format video sources the A-D converter samples the video signal 810 times during the active horizontal line time. The encoded video can be routed to the display -- bypassing the scan converter. In this mode the symbology read from memory is "or"ed with the real-time encoded video.

For sensors which require scan conversion prior to display, the scan converter write address generator and video A-D sampling times are derived from timing and coordinate data from the sensor. The scan converter read address generator, however, continues in the TV raster mode reading out the scan converter memory and symbol memory in the same 30-frame/second, 60-field/second refresh mode regardless of the write address format and timing.

11.2.3 General Purpose Computer

The general purpose computer shown in figure 64 performs the air data analysis and generates instructions to the symbol generator. The computer also interfaces with the display control console and issues mode control data to the symbol generator and signal processor. For some sensors, the computer may also process sensor coordinate data and transfer this information to the signal processor.

While the general purpose computer could be a separate processor dedicated to the VDS system, it most probably will be one of the computational elements of a disturbed multiprocessor system. The estimated computer configuration would be a 16-bit parallel processor with a large instruction set (including hardware multiply and divide), two-level interrupt structure, four general purpose registers, 1000 word scratch pad memory, and 4000 word read only memory for program storage. The instruction execution time (with the possible exception of multiply and divide) should be about 500 nanoseconds. The computer should be organized around a central data bus which allows data transfer between input or output devices and the scratch pad memory in a single instruction.

The probable implementation of this computer would be 20 or fewer complementary-metal-oxide-semiconductor (CMOS) large-scale-integrated circuits (LSI). This type of circuitry would offer the lowest power dissipation possible at the required speed. However, N-channel MOS LSI would also be a possible implementation of the computer with a probable savings in cost.

11.2.4 Mode Control

The mode control allows the pilot to select the operational mode of the VDS system. The choice of sensor and display format will generally be a function of the operational mode. For example, in the terrain following mode, the radar sensor will be automatically chosen. However in some modes, the pilot will also have a choice of sensors. For example, in a weapon delivery mode the pilot may desire either FLIR or low-level television sensor data. The mode control function could be implemented with software that stored the required series of VDS modes needed for a predetermined mission plan. However, the pilot still would need the capability to override the software control in the event of an unpredicted deviation from the flight plan.

The VDS control panel would also have controls to allow the pilot to designate potential targets. The coordinates of these targets would then be calculated by the general purpose computer and sent to the weapons control system.

One hardware implementation of the VDS controls would be a panel of illuminated push-button switches for mode and sensor selection and a conveniently located joy-stick for target designation. The control panel should be similar to the control panels for all the other display systems in the cockpit.

11.2.5 Symbol Generator

The symbol generator accepts commands from the general purpose computer and converts these commands into data points to be stored in the symbol memory. The first major operation accomplished in the symbol generator is the generation and placement of alphanumeric characters and simple graphic symbols, given a symbol code and an address from the computer. The second operation is to generate a quadrangle area, given the four corner points. This area can be generated in any of several crosshatch patterns. This second operation will generally be used in a degenerate mode where the quadrangle area will be a straight line. In the terrain following, station keeping, and terrain avoidance modes, the quadrangle areas will be irregularly shaped and crosshatched to distinguish the terrain contours at various distances.

Both of these functions can be readily hardware-implemented. Hardware implementation is recommended because of the high speed of the data flow between the symbol generator and the symbol memory. The data speeds would require an unrealistically fast general purpose computer if the symbol generation was all accomplished under software control.

11.2.6 Symbol Memory

The symbol memory stores the information provided by the symbol generator. The data is then read in syncronization with the scan of the display. The symbol data is combined with sensor data and the resulting information stream forms the display image.

The dynamic simulation performed on this contract indicated that the necessary symbol quality does not require the full resolution of the 875 line system. The recommended symbol memory size is 405 by 405 by 1 bits. This is one quarter of the visible elements on the display. Only one bit is required per resolution element, since gray shades are not required. Crosshatching is used to separate areas in the terrain-following and station-keeping modes.

The symbol memory is a 164,000 bit random access memory. It must be organized to write one bit at a time, and read 45 adjacent bits at one time. The parallel read is necessary since the display device uses parallel beams.

If the information in the memory must all be changed at a 30 frame per second rate, a 300 ns write-cycle time would be required. A more cost-effective implementation would be to change the information in the memory only as required by changes in the aircraft situation and to limit the rate of change to 10 frames per second. Under all but the most violent maneuvering conditions, the changes in the aircraft situation in one tenth of a second are barely noticeable on the display because the response time of the eye-brain combination is approximately 0.1 sec. The required memory cycle time is now about 1.2 microseconds. This memory can be implemented using low-power, very-low-cost LSI circuits.

11.2.7 Scan Converter

The scan converter converts the incoming sensor data into a form that is directly acceptable to the display device. For FLIR sensors, this requires the storage of one frame of information which is rewritten as new data arrives. For radar, the process is similar, except that a coordinate conversion from R-θ to rectangular must be performed before the data is stored. For line scan sensors, the scan lines are stored in series to form a "moving-window" type of presentation. The write-address generation for all sensors is performed in the signal processor.

The display device has 810 by 810 visible resolution elements. Three bits are required per element for eight shades of gray, and four bits are necessary per element for nine to sixteen shades of gray. Thus, the memory size is 1.97 million bits for eight shades of gray or 2.62 million bits for nine or more shades. The memory must be organized so data for 45 adjacent resolution elements can be read-out to the display in parallel.

The high bandwidth of some of the sensors (up to 23 mhz) would require a memory write-cycle time of 40 ns if only one element is written at a time. A more practical system would use some input buffering and write four elements at a time. The required cycle time would then be 200 ns, which should be easily implemented.

The desired construction of this memory would be a group of LSI circuits, using complementary MOS technology, having 810x3 bits per chip. 810 of these circuits would be required for a system with eight shades of gray. The chip-select addressing and information routing would be done with bipolar MSI circuits.

11.2.8 Display Electronics

The electronic subsystems described in the previous sections would, in general, be present in a VDS system using any display device. The DIGISPLAY driving electronics, which are unique to this example system, are discussed in greater detail in the following sections.

11.2.8.1 Display Scanning Electronics

During the WRITE sequence the display device is scanned in a TV raster mode. The scanning and modulation functions are performed by five plates identified earlier in section 11.1.

The horizontal scanning is performed by plate H_1 in conjunction with the modulator plate. H_1 has 18 segments each of which when ON enables 45 modulator beams. The ON state is achieved by forward biasing the plate segment to a potential of +90 volts relative to the filament potential. In the writing sequence only one of the 18 H_1 segments is ON at a time. The other 17 segments are in the OFF state which corresponds to a potential of -30 volts relative to the filament potential. The potentials for the ON and OFF states are supplied by transistor switches. These switches are of a special design to supply the large currents required to switch the capacity of the plate segments.

The effective capacities involved for the various plates and the times allowed for switching are shown in Table 46.

TABLE 46 VDS 810x810 SWITCHING AND MODULATOR PLATE CAPACITIES AND SWITCHING TIMES

PLATE	NO. OF SEGMENTS	EFFECTIVE CAPACITY pf	TIME TO SWITCH μsec
MOD*	45	1340	0.45
H_1	18	1350	0.45
V_1	9	2670	7.37
V_2	9	2890	7.37
V_3	10	6010	7.37

*The modulator plates are driven by linear modulator amplifiers with analog gray scale signals.

The V_1, V_2 and V_3 plates perform the vertical decoding.

The scanning of the raster starts in the middle of the first line on the odd line numbered field and at the beginning of line two on the even line numbered field. The odd field ends at end of line number 809. The even field ends at the middle of line number 810 (not shown in waveforms).

11.2.8.2 Display Gray Scale Modulation Electronics

Conversion of the incoming video gray scale signal data into gray shade on the display is accomplished by the combination of a D-A converter and a linear amplifier which drives each of the 45 modulator plate segments.

Digital video signal data from the scan converter arrives on nine transmission line pairs. The data consists of five three-bit words; each word is the digital gray shade for a picture element. The incoming data are shifted into shift registers so that each line pair provides one bit of data in serial form for each of fifteen picture elements and a total of 45 three-bit words are accumulated in one 1.73 μsec clock period of the display. The 45 words are then shifted into a holding register which drives the D-A converters in parallel while the next 45 words are being entered into the shift register.

The digital input from the holding register consists of the three-bit word. The D-A converter consists of an open collector decoder, selected weighting resistors and a common-base amplifier stage.

The decoder provides separate outputs for each gray shade. This allows weighting of the output for each gray shade to enhance the usable dynamic range for a given number of gray steps.

The common base output stage Q_1 couples the weighted analog current to the modulator amplifier input. A video gain control which is common to all channels allows adjustment of the magnitude of the analog current by adjusting the base voltage of Q_1. A feedback amplifier converts the analog current into an analog voltage suitable for driving the modulator plate segments. A block diagram of the D-A converter and modulator is shown in figure 67.

The display device modulator transfer function plotted from measured data on a 512x512 device is shown in figure 68.

The entire dynamic range occupies a ΔV above cathode potential of approximately 30V. Since the cathode (filament) potential is approximately +32V above ground, the modulator output potential dynamic range is from +32 to +62 volts.

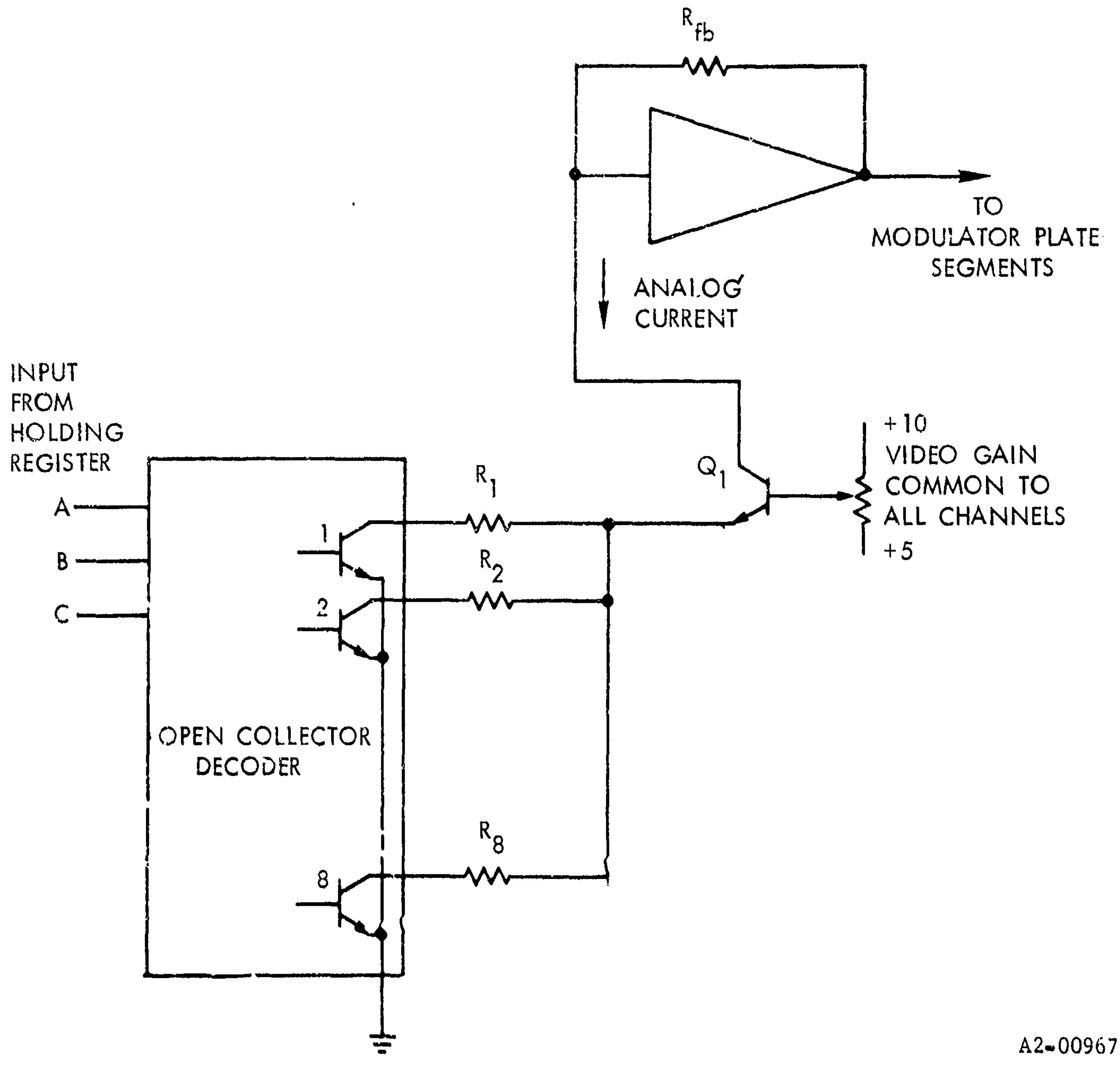


FIGURE 67 BLOCK DIAGRAM D-A CONVERTER AND MODULATOR

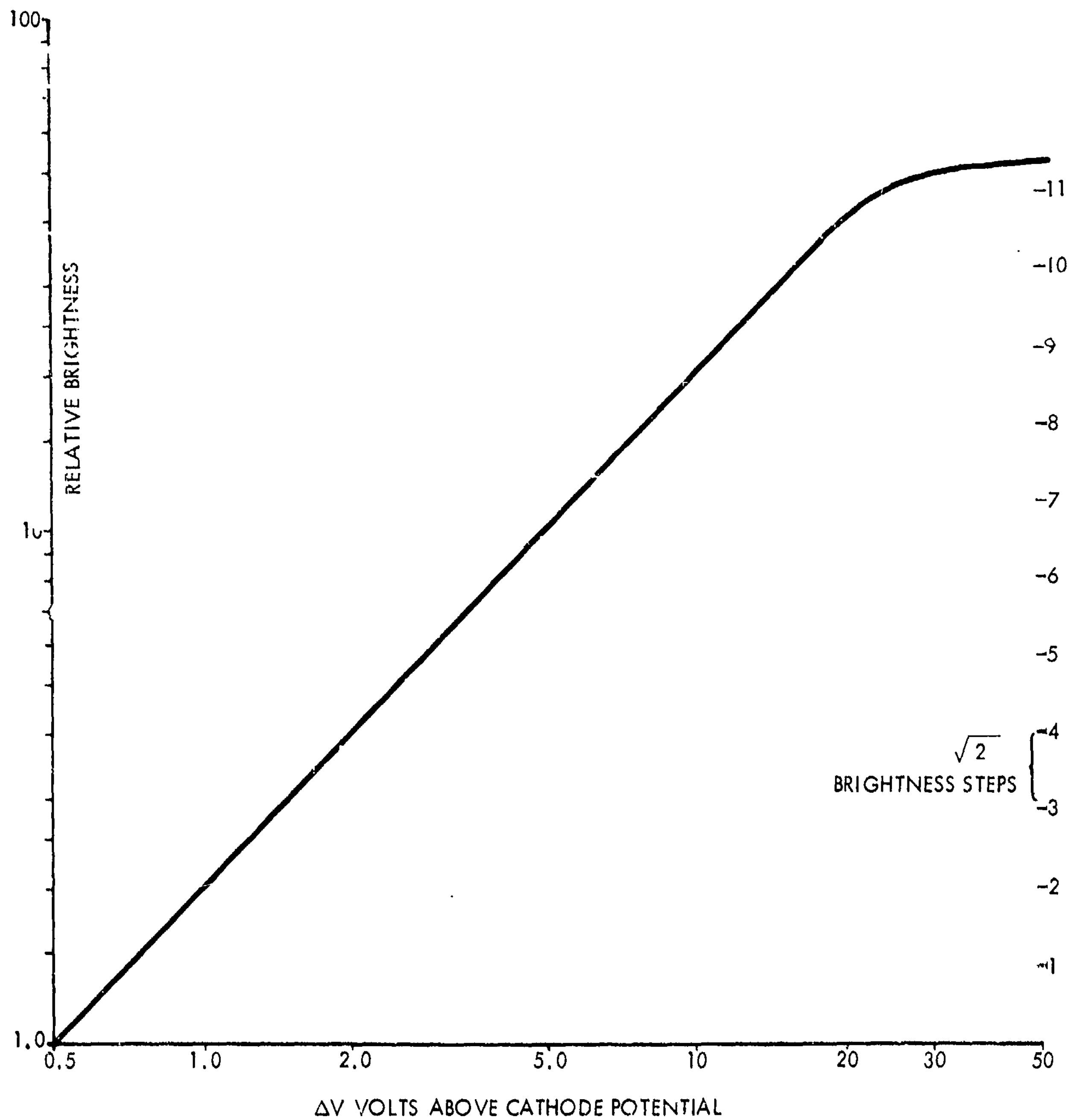


FIGURE 68 - MODULATOR TRANSFER CURVE

11.2.8.3 Display Storage Electronics

The display storage electronics performs the mode sequencing to permit incoming video data to be written onto the storage target, the written data to be displayed on the phosphor during the FLOOD mode and the selective erasure of the "old" field data prior to the writing of the next field of incoming data.

A block diagram of this electronics is shown in figure 69.

The storage sequence waveforms are shown with the system waveforms in figure 66. These are VCE, VST and VC waveforms and FLOOD or ERASE waveforms used to switch the V_1, V_2 and V_3 switches and the H_1 modulators. In the FLOOD mode all beams are turned ON to display the stored data on the phosphor. The FLOOD or ERASE signals also are used in the flood gun to control segment switching and unblanking. In the ERASE mode selective erasure of the "old" field (even numbered lines in figure 66 waveforms) is accomplished so that new data may be written on the storage target during the upcoming even field.

The VCE waveform also shows that electrons passing through the storage mesh during the ERASE mode will be repelled and will not reach the phosphor.

11.2.8.4 Display Power Supply

The display system requires a number of regulated d.c. output voltages, some of which must "float" with respect to the system ground. The system also requires some regulated d.c. output voltages which have very large output currents but low duty cycles. In order to achieve high overall electrical efficiency and minimum weight and size, the power supplies will be divided into two types:

a) A high frequency, voltage regulated a.c. inverter will provide square wave outputs which will drive point-of-load supplies, floating supplies and those supplies that have nearly constant loads. The a.c. inverter will be powered by a driven switching regulator which receives its input from a three-phase half-wave rectifier operating directly from the Y connected 400 Hz line.

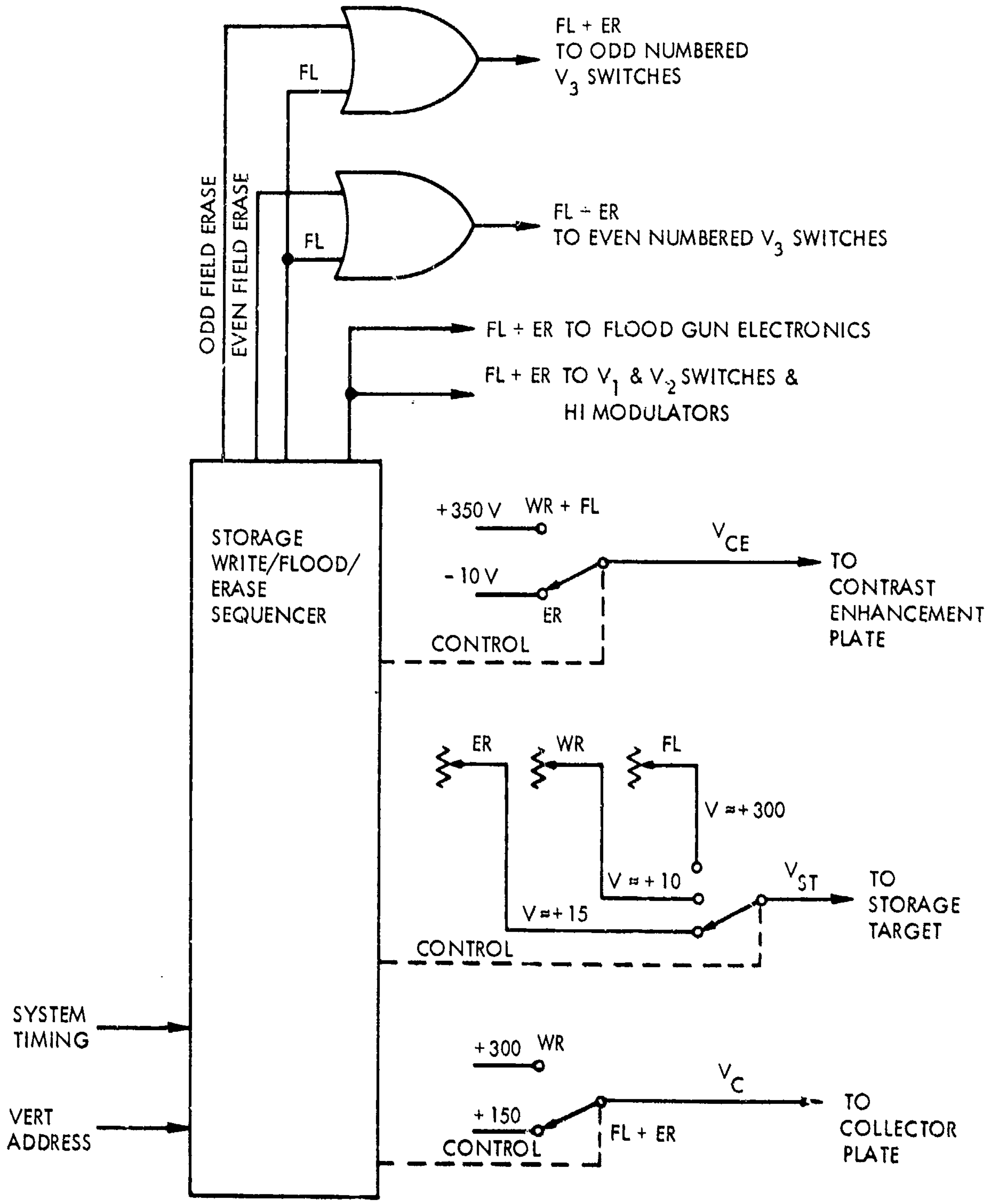


FIGURE 69 · VDS DISPLAY STORAGE ELECTRONICS BLOCK DIAGRAM

b) A 400 Hz three-phase step down transformer supply with six-phase half-wave rectifiers which will power the flood gun electronics where the high current, low duty cycle loads are encountered.

A block diagram of the display power system is shown in figure 70.

The HF inverter-switching regulator combination will be driven by a system timing waveform which is synchronous with the display scanning rate. The inverter frequency is the same as the horizontal line rate

$$f = \frac{1}{38.09 \times 10^{-6}} \approx 26 \text{ KHz}$$

The same frequency will be used to drive the switching regulator.

By causing both the HF inverter and the switching regulator to be synchronous with the scanning process, beats between the power and scanning frequencies will be avoided

The 26 KHz power supply frequency is also desirable from the efficiency, weight, and volume standpoints. Tape cores and ferrite cores may both be used at this frequency as required, with toroid tape and ferrite toroid or cup shapes being desirable for EMI reduction.

The switching regulator d.c. input to the HF inverter will be regulated so that the a.c. inverter output voltage will be nearly constant. The rectified outputs of the inverter will also be nearly constant. The switching regulator will be fold-back current-limited so that transient faults or overload will not lead to catastrophic failure.

The various d.c. loads will be served by small transformer-rectifier supplies with additional protective circuits as required to ensure system reliability.

The supplies which require "floating" outputs such as the filament supply will require specially wound cores to minimize capacity from the output winding to the primary or to ground.

The phosphor supply will be powered from the a.c. inverter and will employ a multiplier to step up the secondary voltage. The phosphor supply load has a low duty cycle. The overall load on the a.c. inverter, however, is kept nearly constant by the fact that the filament supply is turned OFF during the FLOOD and ERASE modes and that the control plate switches are not switching during these modes.

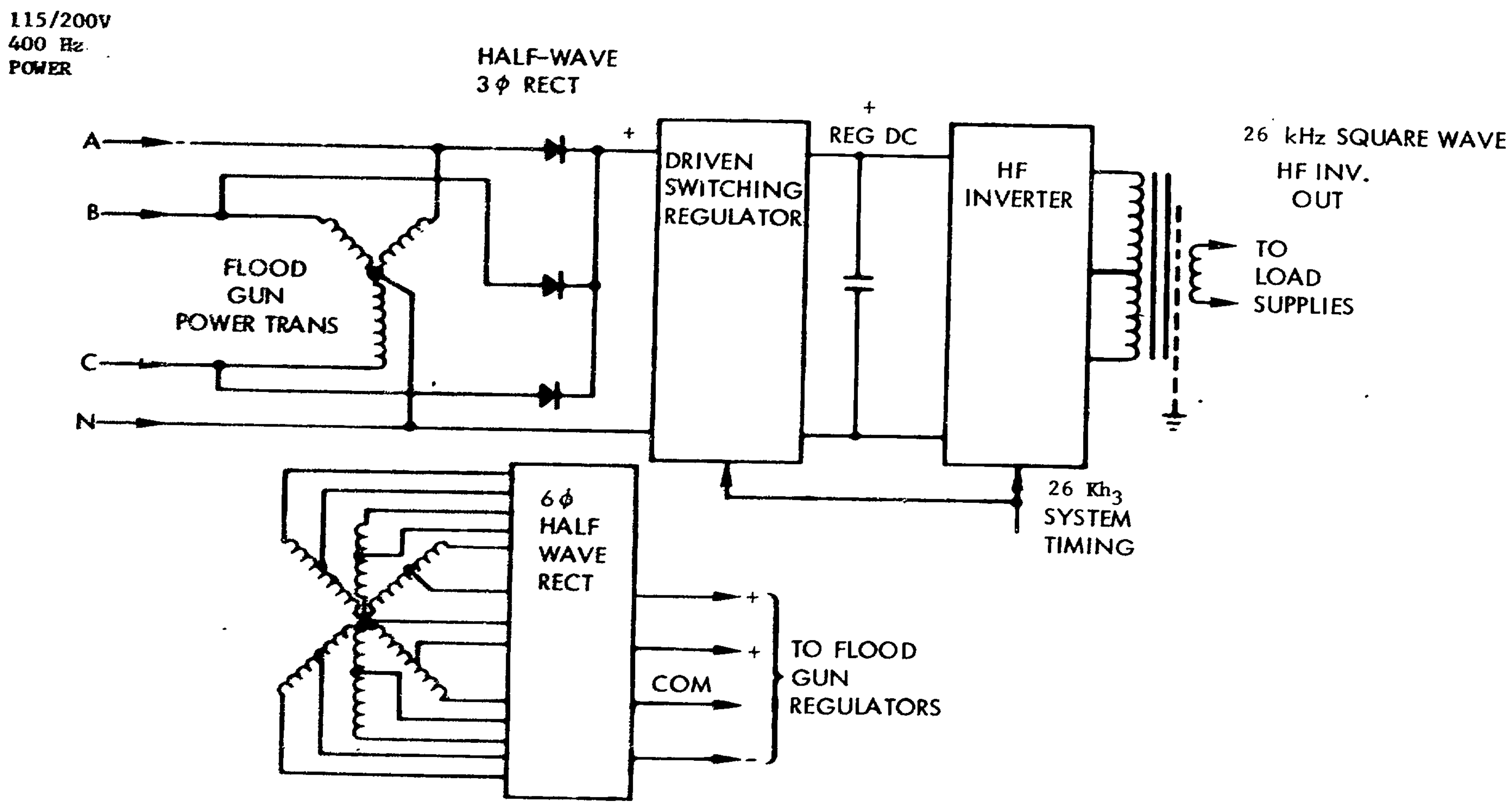


FIGURE 70 - BLOCK DIAGRAM VDS DISPLAY POWER SYSTEM

The step-down transformer type supply for the flood gun power requires a three-phase transformer with center-tapped secondaries. This allows a star connection with six-phase, half-wave rectifiers. This connection gives a very low unfiltered ripple and permits operation of the series regulators (see figure 70) without any ripple filter components.

The nominal load while writing is about one-eighth of the peak load during FLOOD or ERASE modes due to the segmentation of the flood gun.

The step-down transformer and rectifier assemblies will require magnetic shielding to minimize coupling to the display device and to other electronic assemblies.

APPENDIX I

PERFORMANCE ANALYSIS FOR A TWO-DIMENSIONAL DISCRETE SCANNER

I.1 STATEMENT OF PROBLEM

Determination of the modulation transfer function for the discrete scanner would greatly facilitate the design and evaluation of systems employing the scanner in combination with other optical and electronic components. Unfortunately the discrete scanner does not lend itself to a simple MTF analysis of the kind which often suffices for devices which perform spatially continuous transformations. The basic concept of MTF analysis is the preservation, under the transformation produced by the device, of the individual frequency components which comprise an input field. As a result of the transformation the Fourier components generally experience a frequency dependent reduction of modulation and a phase change, but their sinusoidal structure is otherwise unaltered. A sampling device, such as the area scanner, transforms each Fourier component of a continuous input field into a sequence of discrete pulses. Each component thus assumes a complex structure characterized by a multi-component or even continuous Fourier spectrum of its own.

The techniques of Fourier analysis are still applicable in this situation but the MTF must be generalized. The generalized transform function should be formulated so as to be applicable to both discrete and continuously scanning devices. In the spatial domain, a true continuously scanning device is indistinguishable from a device like a lens, which does not scan at all. Most electron beam devices employ a scan continuous in only one dimension. Basic techniques of information enhancement such as aperture compensation should also be anticipated in the formulation of the generalized transfer function.

In order to facilitate preliminary performance evaluations an approximate MTF is calculated for the discrete scanner in this Appendix. In the course of the calculations the "fictitious" nature of an MTF for a discrete sampling device is illustrated, and an hypothetical technique is postulated which circumvents this difficulty by processing the output of the discrete scanner. This procedure leads to an estimate of the optimum MTF for the discrete scanner.

A conclusive analysis of the comparative performance of the discrete scanner and other devices must incorporate other factors beside the frequency response;

e.g., signal-to-noise ratio, contrast, total information content, and possibly other factors which affect the fidelity of a reproduction. Discrete and quasi-continuous scanners each appear to offer some advantage in disparate aspects of their operation, and the overall performance of each relative to the other requires very careful evaluation. For example, quasi-continuous devices have the obvious advantage that all of the information field is sampled at the same response level. A discrete device samples various areas in the input field with differing response even when the beams overlap, although of course the disparity in the response between points at one of the beam center positions and intermediate points is reduced as the overlap is increased. On the other hand, in a two-stage device which reads, transmits and recomposes a scene at a remote location, the discrete scanning device appears to have an inherent advantage. If the reading and writing stages are both continuous scanners, the overall response function is the convolution of the two individual response functions, assuming infinite passband signal transmission. A point target in the input is reproduced with the full width of the composite response function. If the reading and writing stages are discrete scanners, a point target in the input produces a signal from the reading stage which is received by the write stage and causes the latter to write, in one of the discrete locations assumed by its beam, a signal whose width is that of the write beam alone. The approximate MTF calculation for the discrete scanner follows.

I.2 ANALYSIS OF MTF PERFORMANCE

It is convenient to consider first an hypothetical device which is characterized by a gaussian response function and which scans continuously in both the x and y directions. The instantaneous position of the beam is given by x_r, y_r, as indicated in figure 71.

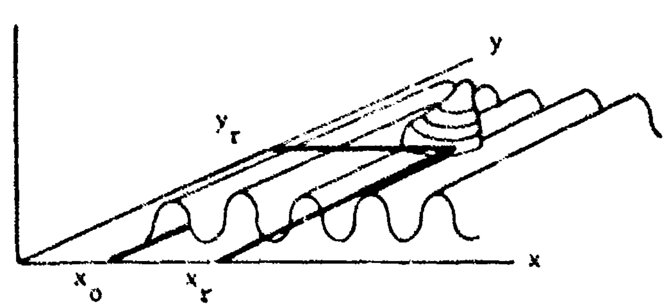


FIGURE 71

The response function is given by

$$R_{ff}(x,y) = Be^{-a^2\left[(x-x_1)^2 + (y-y_1)^2\right]} \tag{1}$$

Also shown in figure , is a section of one of the frequency components of the input field, i.e., a cosine bar pattern of spatial frequency ω, which is centered with its bars parallel to the y axis and which has been phased as . Denote the bar pattern by

$$f(x) = A_0 + A_1 \cos \omega(x-x_0) \tag{2}$$

The modulation of this frequency component is A_1/A_0.

Define the parameters

$$\xi = a(x-x_0), \quad \bar{\xi} = a(x_1-x_0), \quad \eta = ay, \quad \bar{\eta} = ay_1$$

Then the response function and the cosine bar pattern can be rewritten as follows

$$R_{ff}(\xi,\eta) = Be^{-\left[(\xi-\bar{\xi})^2 + (\eta-\bar{\eta})^2\right]} \tag{3}$$

$$f_0(\xi) = A_0 + A_1 \cos \frac{\omega}{a}\xi \tag{4}$$

The scan produces a signal given by the convolution of these two functions

$$e_{ff}(\bar{\xi},\bar{\eta}) = B\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-\left[(\xi-\bar{\xi})^2 + (\eta-\bar{\eta})^2\right]}\left[A_0 + A_1 \cos\frac{\omega}{a}\xi\right]d\xi\, d\eta \tag{5}$$

A simple integration yields

$$e_{ff}(\bar{\xi}) = A_0 B \frac{\pi}{a^2} + A_1 B \frac{\sqrt{\pi}}{a} \int_{-\infty}^{\infty} e^{-(\xi-\bar{\xi})^2} \cos\frac{\omega}{a}\xi\, d\xi \tag{6}$$

Make the substitution $t = \xi - \bar{\xi}$ and expand the expression, $\cos\frac{\omega}{a}(t+\bar{\xi})$, which results

$$e_{ff}(\bar{\xi}) = A_0 B \frac{\pi}{a^2} + A_1 B \frac{\sqrt{\pi}}{a} \int_{-\infty}^{\infty} e^{-t^2}\left[\cos\frac{\omega}{a}t \cos\frac{\omega}{a}\bar{\xi} - \sin\frac{\omega}{a}t\, \sin\frac{\omega}{a}\bar{\xi}\right]dt$$

Define

$$\phi_c(\omega) = \frac{\int_0^\infty e^{-a^2\rho} \cos \omega\rho \, d\rho}{\int_0^\infty e^{-a^2\rho} \, d\rho} \tag{7}$$

and

$$\phi_s(\omega) = \frac{\int_0^\infty e^{-a^2\rho} \sin \omega\rho \, d\rho}{\int_0^\infty e^{-a^2\rho} \, d\rho} \tag{8}$$

These are respectively the cosine Fourier transform and the sine Fourier transform of the response function $e^{-a^2 v^2}$.

In terms of these functions

$$e_{rc}(\xi) = A_0 B \frac{v}{a^2} + A_1 B \left(\frac{\sqrt{v}}{a}\right)^2 \left[\phi_c(\omega) \cos \omega\xi + \phi_s(\omega) \sin \omega\xi\right]$$

which can also be written in the following form.

$$e_{rc}(\xi) = A_0 B \frac{v}{a^2} + A_1 B \frac{v}{a^2} C(\omega) \cos \left[\omega\xi - \phi(\omega)\right] \tag{9}$$

where

$$|C(\omega)| = \left(\phi_c^2 + \phi_s^2\right)^{\frac{1}{2}} \tag{10}$$

and

$$\tan \phi(\omega) = \frac{\phi_s}{\phi_c} \tag{11}$$

Thus, the original cosine function is reproduced as a cosine function. Since $e^{-a^2 v^2}$ is an even function, $\phi_s(\omega) = 0$ and there is no phase shift.

The modulation of the transformed cosine function is given, as before, by the ratio of the amplitude of the oscillatory component to that of the d.c. component.

$$\text{modulation} = \frac{A_1 B \frac{\pi}{\alpha^2} C(\omega)}{A_o B \frac{\pi}{\alpha^2}} = \tau_c(\omega).$$

The normalized cosine transform of the gaussian response function, calculated from Equation (7) is

$$\tau_c(\omega) = e^{-\omega^2/4\alpha^2} \qquad (12)$$

Each cosine component of the initial input field which is oriented like the sample component which has been considered produces an analagous result. Equation (12) thus represents the frequency dependence of the modification of the modulation for all frequency components oriented with their maxima parallel to the y-axis. The modulation transfer function should be calculated by averaging this function over all possible orientations. But this averaging process is often omitted and this practice is followed here. Then Equation (12) represents the MTF for the hypothetical continuous scanning device.

Turning now to consideration of the discretely scanning area device, we consider the transformation of the same sample frequency component,

$$f_o(\xi) = A_o + A_1 \cos \omega\xi$$

The instantaneous response function is also unchanged:

$$b_{rd}(\xi,\eta) = Be^{-\alpha^2\left[(\xi-\bar{\xi})^2 + (\eta-\bar{\eta})^2\right]}.$$

But the beam now advances in discrete steps of length Δx in the x-direction and Δy in the y-direction. In the process the closest approach which the beam makes to the bar pattern reference position, x_o, is Δx_o.

It can be shown that the signal produced by the discretely scanning beam is given by

$$s_{rd}(\bar{\xi},\bar{\eta}) = \sum_m \sum_n s_{rc}\,(\Delta x_o + m\Delta x,\ n\Delta y)\ \ (\bar{\xi}-\Delta x_o-m\Delta x,\ \bar{\eta}-n\Delta y) \qquad (13)$$

Here $s_{rc}(\Delta x_o + m\Delta x, n\Delta y)$ is the function previously calculated for the continuous scan. (The subscript c becomes d in $s_{rd}(\bar{\xi},\bar{\eta})$ to denote the change from a continuous to a discrete scan.) $\delta(\bar{\xi} - \Delta X_o - m\Delta x, \bar{\eta} - n\Delta y)$ is the two dimensional Dirac delta function. It is equivalent to $\delta(\bar{\xi} - \Delta x_o - m\Delta x)\delta(\bar{\eta} - n\Delta y)$.

A typical example of the relationship between $s_{rc}(\bar{\xi})$ and $s_{rd}(\bar{\xi})$ is shown (in one dimension) in figure 72. This example corresponds to a more general input than a single cosine wave.

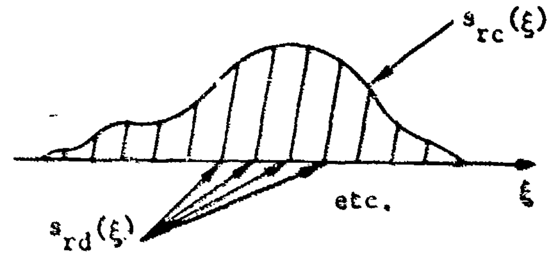


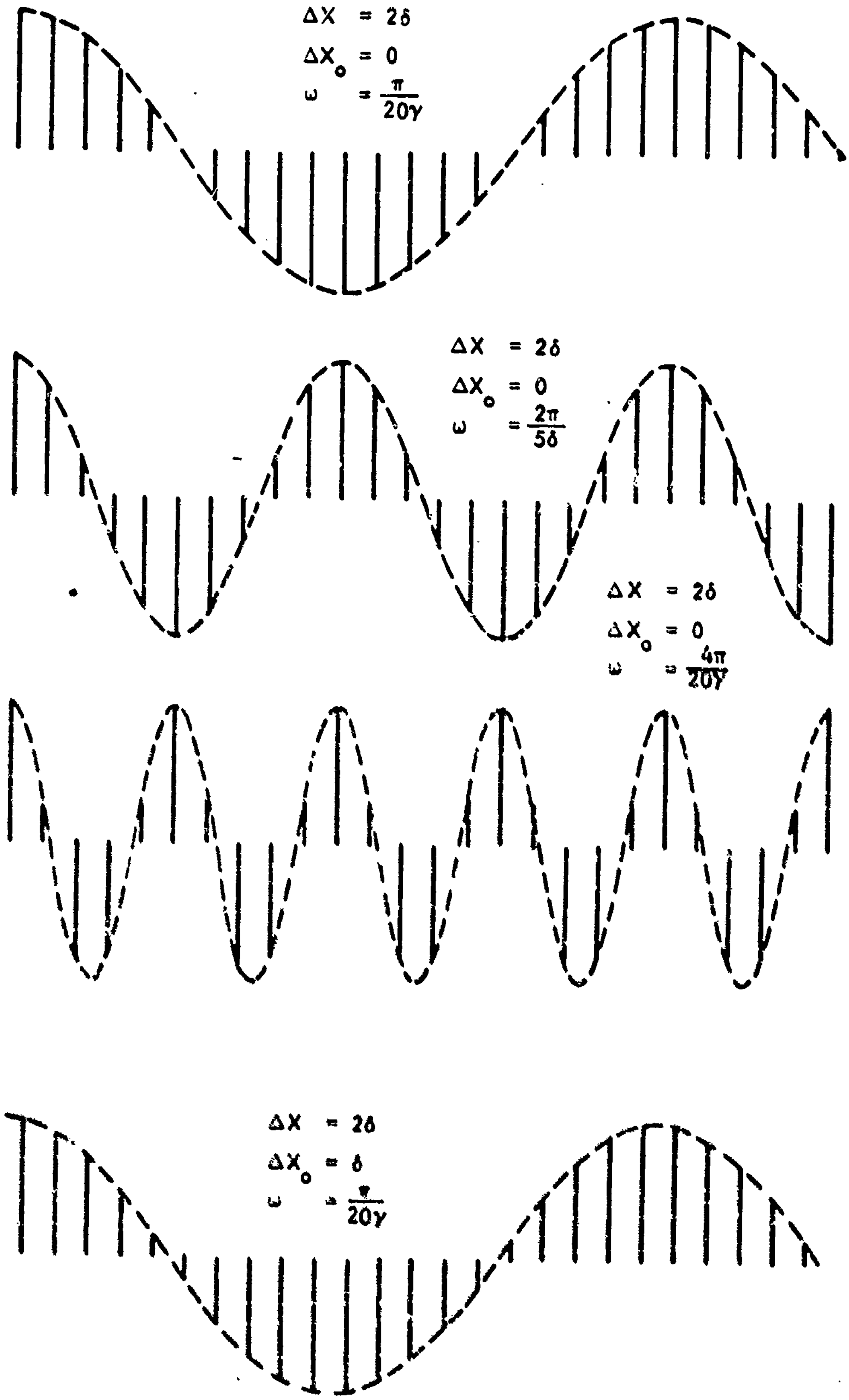
FIGURE 72

Upon substitution of $s_{rc}(\bar{\xi},\bar{\eta})$ into Equation (13) and carrying out the indicated operations the result is

$$s_{rd}(\bar{\xi}) = \sum_m \left[A_o B \frac{\pi}{\sigma^2} + A_1 B \frac{\pi}{\sigma^2} e^{-\frac{\omega^2}{4\sigma^2}} \cos\omega(\Delta x_o + m\Delta x)\right] \cdot \delta(\bar{\xi} - \Delta x_o - m\Delta x)$$

The signal is a sequence of sharp pulses modulated by a cosine wave with the same frequency as the input wave, the modulation of which has been reduced by the same factor, $e^{-\omega^2/4\sigma^2}$, as for the case of the continuous scan. The cosine wave has not been preserved and the MTF is not defined in the usual sense.

In figure 73 several examples of $s_{rd}(\xi)$ are shown. Since the factor $e^{-\omega^2/4\sigma^2}$ occurs in $s_{rd}(\xi)$ as well as $s_{rc}(\xi)$, the discrete scan modulation can never exceed that associated with the continuous scan. In order to estimate the minimum possible reduction of the continuous scan MTF which the use of a discrete scan effects, consider the following scheme. Postulate the existence of a device which can separate the individual frequency components in the composite



$\Delta X = 2\delta$
$\Delta X_o = 0$
$\omega = \frac{\pi}{20\gamma}$
$\Delta X = 2\delta$
$\Delta X_o = 0$
$\omega = \frac{2\pi}{5\delta}$
$\Delta X = 2\delta$
$\Delta X_o = 0$
$\omega = \frac{4\pi}{20\gamma}$
$\Delta X = 2\delta$
$\Delta X_o = \delta$
$\omega = \frac{\pi}{20\gamma}$

FIGURE 73

signals into pulse trains such as those shown in the individual parts of figure 73. This device must also be able to determine the frequency of the cosine wave envelope of each such train of pulses by counting the number of times per second that the signal changes from positive to negative and vice versa. Moreover it must measure the height of the maximum pulse in the positive and negative half of each cycle. If it associates a cosine wave with each frequency it senses these waves will display a reduction in modulation corresponding to the mismatch of the sampling positions which produce the peak pulses with the maxima of the respective cosine waves. An MTF calculation based on these considerations was used. It employed only information which is actually contained in the pulse trains. A physical realization of the scheme might be difficult or even impossible. The calculation yields an estimate of the minimum deterioration of the MTF which would occur if the frequency and peak amplitude information could be fully utilized.

A graphical procedure was used to make calculations based on this scheme. A number of cycles of a cosine wave were plotted and the amplitude read off of the wave at a sequence of positions separated by Δx and beginning at a given Δx. The peak amplitudes were averaged. Δx was then scaled to correspond to a wave of different frequency and the process repeated, over and over again for a sequence of frequencies. In each case the steps were carried over enough cycles so that the process ended at the same phase angle at which it started. This corresponds to the processing device averaging the peak amplitude over a large number of complete cycles. Calculations were actually made at frequencies where the step size was commensurate with a small number (less than 10) whole cycles.

III. RESULTS

The results are presented in figure 74. A few words of explanation will facilitate interpretation of the figure.

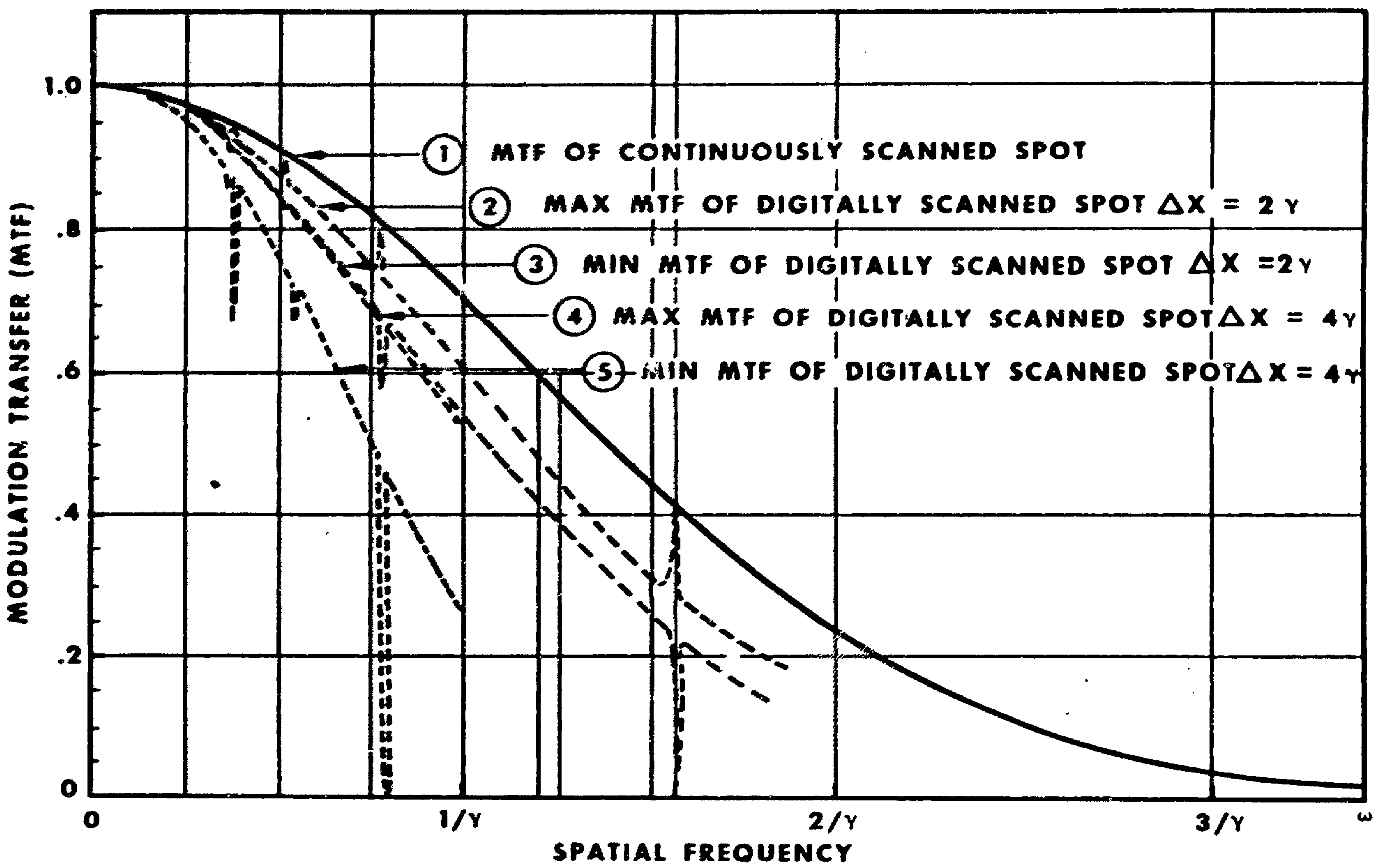


FIGURE 74 COMPARISON OF MTF PERFORMANCE OF DIGITALLY VS CONTINUOUSLY SCANNED SPOT

The response function for the device was given as $b_r(\xi,\eta) = Be^{-\alpha^2\left[(\xi-\xi)^2 + (\eta-\eta)^2\right]}$. This function has a half-width $\gamma = \frac{\sqrt{\ln 2}}{\alpha}$.

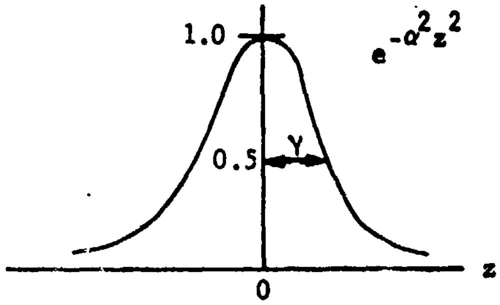
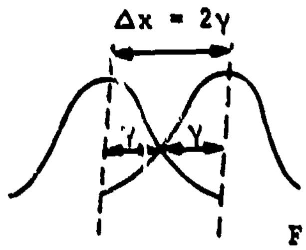


FIGURE 75

The MTF for the continuously scanning device was given by the gaussian function $e^{-\omega^2/4\alpha^2}$. The halfwidth of this function is $\Gamma = 2\alpha\sqrt{\ln 2}$. Thus the halfwidths of the two functions are related as follows:

$$\Gamma = \frac{2 \ln 2}{\gamma} = \frac{1.386}{\gamma}.$$

By the time the frequency has reached double this value the continuous scan MTF has dropped to so low a value as to be of little further interest. Moreover, the whole scheme fails for frequencies beyond about 2Γ because the corresponding cosine waves are no longer sampled at least once during each half-cycle. The frequency range of interest can therefore be expressed conveniently in units of $1/\gamma$. The period of a given cosine component is of course given by $P = \frac{2\pi}{\omega}$.



A scan was chosen for the calculation in which the scan step was equal to two times the half-width of the response function.

FIGURE 76

Note that the minimum separation, Δx_0, of some one of the beam positions from the zero phase position of a given frequency component cannot exceed $\Delta x/2$ or $P/2$, whichever is smaller.

In figure 74 the continuous scan MTF ($e^{-\omega^2/4\alpha^2}$) is drawn as a solid line, curve 1. The uppermost dotted line, curve 2 represents the pseudo-MTF for a discrete scan with $\Delta x = 2\gamma$ and Δx_o always equal to zero; i.e., with exact registration of at least one beam position with the zero phase position for each frequency component. This situation, which obviously cannot be realized in general, produces maximum modulation. In particular, when $\Delta x = P/2n$ or $\omega = \pi\Delta x/n$ where n is an integer, the scanning beam hits each maximum and minimum of every frequency component. In this case there is no reduction of modulation relative to the continuous case, and sharp peaks occur on the curve.

The lower dotted line, curve 3, corresponds to a discrete scan with $\Delta x = 2\gamma$ and maximum Δx_o for each frequency component. It represents the worst possible case and, as before, this extreme is not physically possible (or at least extremely unlikely). When $\omega = \pi/n\Delta x$ with maximum Δx_o the maximum reduction in the modulation occurs, and sharp valleys occur on the curve. For $\omega = \pi/\Delta x$ and $\Delta x_o = \frac{\Delta x}{2}$, all of the sampling points are at the zeroes of the corresponding cosine wave and the MTF plunges to zero. Curves 4 and 5 are similar to curves 2 and 3 but they represent the case where $\Delta x = 4\gamma$.

Any real case corresponds to a distribution of Δx_o between zero and the maximum value it can attain, and will yield an MTF falling somewhere between the maximum and minimum response curves for each case.

The curves in figure 74 are plotted in terms of the parameter $1/\gamma$ and are valid for any beam half-width γ as long as $\Delta x = 2\gamma$, or $\Delta x = 4\gamma$.

EVALUATION FORM #1

Display Technique DIGISPLAY

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	80	3	100 dots/inch	5
2. Spot Size	5 mils	3	6.25 mils	2	5 mils	3
3. Screen Size	9.5 in square 8.93x1[illegible] elements	4	6 inch,512x512	2	10 inch	4
4. Brightness	1300 FL minumum	7	350 FL	-2.6	1300 FL	2.8
5. Uniformity	± 10%	5	±12%	4	±10	5
6. Contrast Ratio	23 - 1	2	23	2	23 - 1	2
7. Gray Scale	10 shades of gray	8	8	4	10	8
8. Color	2 or more colors	1	2	1	2	1
9. Scanning Rate	20 MHz	12	5 MHz	3	20 MHz	12
10. Storage	2 minutes	1	30 sec	1	30 sec	1
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	1500 hours	3.3	5000 hours	12
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique DIGISPLAY

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards		Can be ruggedized	
13. Temperature and Humidity	Meets MIL-E-5400	2	No	0	Yes	2
14. Shock	Meets MIL-E-5400	2	No	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	1.5 Ft^3	2	0.5	4
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	75	2.2	50	3
20. Average Power Consumption	<100 watts	3	400	-0.6	160	2.3
21. Peak Power Consumption	<1 KW	1	450 watts	1	250 watts	1
22. Production Feasibility	Easily produced	5	Present technology	3	Present	4
23. Design Complexity	Low complexity Few parts	5	Moderate	3	Moderate	4
24. Production Cost	Low cost (50K)	5	75K	3	50K	4
			TOTAL POINTS	39		90
			FINAL AVERAGE		65	

EVALUATION FORM #1

Display Technique LIQUID CRYSTAL DISPLAY

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	100	5	100	5
2. Spot Size	5 mils	3	5 mils	3	5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	2 x 18 elements	0	1000 x 1000 elements	4
4. Brightness	1300 FL minimum	7	Source Dependent 2500 FL	7	Source Dependent 2500 FL	7
5. Uniformity	± 10%	5	Est. ±20%	0	±12%	4
6. Contrast Ratio	23 - 1	2	25 - 1	2	25 - 1	2
7. Gray Scale	10 shades of gray	8	8	4	10	8
8. Color	2 or more colors	1	2	1	2	1
9. Scanning Rate	20 MHz	12	5 MHz	3	20 MHz	12
10. Storage	2 minutes	1	30 minutes to 3 weeks	1	30 minutes to 3 weeks	1
11. Reliability MTBF	2000 hours system 50% hours disp. and elec.	12	1000 hours	2	2700 hours	6.3
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique LIQUID CRYSTAL DISPLAY

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards			
13. Temperature and Humidity	Meets MIL-E-5400	2	-10° to 50°C	0	With difficulty	1
14. Shock	Meets MIL-E-5400	2	No	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	1.5 Ft^3	2	0.5 Ft^3	4
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	< 50 pounds	3	< 50 pounds	3
20. Average Power Consumption	<100 watts	3	< 100 watts	3	< 100 watts	3
21. Peak Power Consumption	<1 KW	1	< 1 KW	1	< 1 KW	1
22. Production Feasibility	Easily produced	5	No theoretical limitations	1	Complex but should be ultimately feasible	2
23. Design Complexity	Low complexity Few parts	5	Extremely Complex Addressing	1	Extremely Complex Addressing	2
24. Production Cost	Low cost (50K)	5	~100K	2	~ 50K	4
			TOTAL POINTS	44		83
			FINAL AVERAGE		64	

EVALUATION FORM #1

Display Technique LED

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	60	1	100	5
2. Spot Size	5 mils	3	8 mils	0.6	5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	6 inches	2	10 inches	4
4. Brightness	1300 FL minimum	7	25 FL Equiv. to 100 FL	-7	300 FL Equiv. to 1200 FL	2.5
5. Uniformity	± 10%	5	±15%	2.5	±12%	4
6. Contrast Ratio	23 - 1	2	23	2	23	2
7. Grey Scale	10 shades of gray	8	10	8	10	8
8. Color	2 or more colors	1	2	1	2	1
9. Scanning Rate	20 MHz	12	5 MHz	3	20 MHz	12
10. Storage	2 minutes	1	No	0	No	0
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	2780 hours	6.4	2780 hours	6.4
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique LED

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400					
13. Temperature and Humidity	Meets MIL-E-5400	2	Yes	2	Yes	2
14. Shock	Meets MIL-E-5400	2	Yes	2	Yes	2
15. Vibration	Meets MIL-E-5400	2	Yes	2	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	Yes	2	Yes	2
17. Volume	<1.5 Ft^3	4	1 Ft^3	3	1 Ft^3	3
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	75 pounds	2.2	75 pounds	2.2
20. Average Power Consumption	<100 watts	3	>2000 watts	-3	>1000 watts	-3
21. Peak Power Consumption	<1 KW	1	>1 KW	0	>1 KW	0
22. Production Feasibility	Easily produced	5		2		2
23. Design Complexity	Low complexity Few parts	5		2		2
24. Production Cost	Low cost (50K)	5	100K	2	100K	2
		TOTAL POINTS		38		68
			FINAL AVERAGE		53	

EVALUATION FORM #1

Display Technique FERROELECTRIC BISMUTH TITANATE

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	< 60	0	100	5
2. Spot Size	5 mils	3	5 mils	3	5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4		0	1000x1000 elements	4
4. Brightness	1300 FL minimum	7	Source Dependent 2500 FL	7	Source Dependent 2500 FL	7
5. Uniformity	± 10%	5	Est. ±24%	-2	Est. ±12%	4
6. Contrast Ratio	23 - 1	2	20 - 1	1.5	23 - 1	2
7. Gray Scale	10 shades of gray	8	2	-8	10	8
8. Color	2 or more colors	1	1	0	Possible 2	1
9. Scanning Rate	20 MHz	12	20 MHz	12	20 MHz	12
10. Storage	2 minutes	1	Until erased	1	Until erased	1
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	Very early in R&D Stage Est. ~800 hours	-2	1000 hours	2
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique FERROELECTRIC BISMUTH TITANATE

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards		Can be ruggedized	
13. Temperature and Humidity	Meets MIL-E-5400	2	No	0	Yes	2
14. Shock	Meets MIL-E-5400	2	No	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	~1.5 Ft^3	2	~0.5 Ft^3	4
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	<75 pounds	2.2	<50 pounds	3
20. Average Power Consumption	<100 watts	3	100 watts	3	100 watts	3
21. Peak Power Consumption	<1 KW	1	<1 KW	1	<1 KW	1
22. Production Feasibility	Easily produced	5	Low	1	Low	1
23. Design Complexity	Low complexity Few parts	5	High	1	High	1
24. Production Cost	Low cost (<50K)	5	125 K	1	100 K	2
			TOTAL POINTS	27		76
			FINAL AVERAGE		51	

EVALUATION FORM #1

Display Technique A.C. PLASMA

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	80	3	100	5
2. Spot Size	5 mils	3	6.25 mils	2	5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	6 in., 512×512	2	9.6 in. (10^6 elements)	4
4. Brightness	1300 FL minimum	7	300 FL	-3.5	1000 FL	1.8
5. Uniformity	± 10%	5	±10%	5	±10%	5
6. Contrast Ratio	23 - 1	2	23 - 1	2	23 - 1	2
7. Gray Scale	10 shades of gray	8	4	-4	6	0
8. Color	2 or more colors	1	2	1	2	1
9. Scanning Rate Rate	20 MHz	12	4 MHz	2.4	20 MHz	12
10. Storage	2 minutes	1	2 minutes	1	2 minutes	1
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	1000 hours	2	1000 hours	2
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique A.C. PLASMA

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards		Can be ruggedized	
13. Temperature and Humidity	Meets MIL-E-5400	2	No	0	Yes	2
14. Shock	Meets MIL-E-5400	2	No	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	1.5 Ft^3	2	1 Ft^3	3
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	75 pounds	2.2	50 pounds	3
20. Average Power Consumption	<100 watts	3	400 watts	-0.6	300 watts	0.6
21. Peak Power Consumption	<1 KW	1	1.2 KW	0	<1 KW	1
22. Production Feasibility	Easily produced	5		4		4
23. Design Complexity	Low complexity Few parts	5		4		4
24. Production Cost	Low cost (50K)	5	50 K	4	50K	4
			TOTAL POINTS	36		68
			FINAL AVERAGE		50	

EVALUATION FORM #1

Display Technique LASER

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dot /inch	5	100	5	100	5
2. Spot Size	5 mils	3	5 mils	5	5 mils	5
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	10 inches	4	10 inches	4
4. Brightness	1300 FT minimum	7	800 FL equiv.to 2500 FL	7	800 FL equiv.to 2500 FL	7
5. Uniformity	± 10%	5	±10%	5	+10%	5
6. Contrast Ratio	23 - 1	2	23 - 1	2	23 - 1	2
7. Gray Scale	10 shades of gray	8	10	8	10	8
8. Color	2 or more colors	1	1	0	1	0
9. Scanning Rate	30 MHz	12	20 MHz	12	20 MHz	12
10. Storage	2 minutes	1	No	0	No	0
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	600 hours	-6	1000 hours	+2
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique LASER

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400					
13. Temperature and Humidity	Meets MIL-E-5400	2	No	0	Yes	2
14. Shock	Meets MIL-E-5400	2	No	0	Yes	1
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	1
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	>4.0 Ft^3	-4	4.0 Ft^3	-4
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	550 pounds	-3	350 pounds	-3
20. Average Power Consumption	<100 watts	3	1 KW	-3	600 watts	-3
21. Peak Power Consumption	<1 KW	1	1 KW	0	1 KW	0
22. Production Feasibility	Easily produced	5		2		2
23. Design Complexity	Low complexity Few parts	5		2		2
24. Production Cost	Low cost (50K)	5	100K	2	100K	2
			TOTAL POINTS	39		54
			FINAL AVERAGE		47	

EVALUATION FORM #1

Display Technique E.L.MATRIX

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	60	1	100	5
2. Spot Size	5 mils	3	8 mils	0.6	5 mils	5
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	512x512	2	10 inch 10^6 elements	4
4. Brightness	1300 FL minimum	7	30 FL	-7	50 FL	-7
5. Uniformity	± 10%	5	±14%	3	±12%	4
6. Contrast Ratio	23 - 1	2	23	2	23	2
7. Gray Scale	10 shades of gray	8	10	8	10	8
8. Color	2 or more colors	1	2	1	2	1
9. Scanning Rate	20 MHz	12	5 MHz	3	20 MHz	12
10. Storage	2 minutes	1	No	0	No	0
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	600 hours	-6	800 hours	-2
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique E.L.MATRIX

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400					
13. Temperature and Humidity	Meets MIL-E-5400	2	Yes	2	Yes	2
14. Shock	Meets MIL-E-5400	2	Yes	2	Yes	2
15. Vibration	Meets MIL-E-5400	2	Yes	2	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	Yes	2	Yes	2
17. Volume	<1.5 Ft^3	4	2 Ft^3	1	1 Ft^3	3
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	75 pounds	2.2	50 pounds	3
20. Average Power Consumption	<100 watts	3	>400 watts	-0.6	>400 watts	-0.6
21. Peak Power Consumption	<1 KW	1	<1 KW	1	<1 KW	1
22. Production Feasibility	Easily produced	5		3		3
23. Design Complexity	Low complexity Few parts	5		3		3
24. Production Cost	Low cost (50K)	5	50K	4	50K	4

TOTAL POINTS 33 60

FINAL AVERAGE 47

EVALUATION FORM #1

Display Technique OIL FILM LIGHT VALVE PROJECTION SYSTEM

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	>100	5	>100	5
2. Spot Size	5 mils	3	< 5 mils	3	< 5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	Up to 20 ft.	4	Up to 30 ft.	4
4. Brightness	1300 FL minimum	7	Source Dependent 1700 FL	4.2	Source Dependent 1700 FL	4.2
5. Uniformity	± 10%	5	±14%	3	±10%	5
6. Contrast Ratio	23 - 1	2	100 - 1 (Color: 50 - 1)	2	100 - 1	2
7. Gray Scale	10 shades of gray	8	10	8	10	8
8. Color	2 or more colors	1	3	1	1	0
9. Scanning Rate	20 MHz	12	5 MHz	3	20 MHz	12
10. Storage	2 minutes	1	None	0	None	0
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	1000 hours	2	1000 hours	2
12. Maintainability	1000 hours between adjustments	5	400 hours Modular Construction	2	600 hours	3

EVALUATION FORM #2

Display Technique OIL FILM LIGHT VALVE PROJECTION SYSTEM

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards			
13. Temperature and Humidity	Meets MIL-E-5400	2	0° - 150°C - Optimum temperature is 68°C	0	Can be heated	1
14. Shock	Meets MIL-E-5400	2	7g	0	Can be protected	1
15. Vibration	Meets MIL-E-5400	2	No	0	Can be ruggedized	1
16. EMI and RFI	Meets MIL STD 456	2	Some shielding is incorporated	0	Yes	2
17. Volume	<1.5 ft^3	4	2' D x 2' W x 5' H	-4	2' x 2' x 2'	-4
18. Form Factor	Two or more packages	1	Two major pieces (Base and Head)	1	Base and head	1
19. Weight	<100 pounds	3	460 pounds	-3	155	-0.5
20. Average Power Consumption	<100 watts	3	1650 watts	-3	400 watts	-0.6
21. Peak Power Consumption	<1 KW	1	>1 KW	0	<1 KW	1
22. Production Feasibility	Easily produced	5	525 line system available now	3	Moderate	3
23. Design Complexity	Low complexity Few parts	5	Moderate to high	2	Moderate to high	2
24. Production Cost	Low cost (50K)	5	125 K	1	100 K	2
		TOTAL POINTS		34		57
			FINAL AVERAGE		46	

EVALUATION FORM #1

Display Technique MAGNETO-OPTICS

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	100	5	100 dots/inch	5
2. Spot Size	5 mils	3	5 mils	3	5 mils	3
3. Screen Size	9.5 in. square 8.93x10^5 elements	4	10x10 elements	0	1000x1000 elements	4
4. Brightness	1300 FL minimum	7	Source Dependent 2500 FL	7	Source Dependent 2500 FL	7
5. Uniformity	± 10%	5	Est. ±28%	-4	±20%	0
6. Contrast Ratio	23 - 1	2	30 - 1	2	50 - 1	2
7. Gray Scale	10 shades of gray	8	2	-8	5	-2
8. Color	2 or more colors	1	1	0	2-3	1
9. Scanning Rate	20 MHz	12	20 MHz	12	20 MHz	12
10. Storage	2 minutes	1	2 minutes	1	2 minutes	1
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	1000 hours	2	1000 hours	2
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique MAGNETO-OPTICS

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards			
13. Temperature and Humidity	Meets MIL-E-5400	2	Temp. Dependent (Bitter Soln)	0	With difficulty	1
14. Shock	Meets MIL-E-5400	2	Not Protected	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	Subject to shock vibration	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	Not presently protected	0	Yes	2
17. Volume	<1.5 Ft^3	4	~4 Ft^3	-4	~3.5 Ft^3	-2.7
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	~50 pounds	3	~50 pounds	3
20. Average Power Consumption	<100 watts	3	1 - 2 KW (Light source + elec.)	-3	1 - 2 KW (Light source + elec.)	-3
21. Peak Power Consumption	<1 KW	1	>1 KW	0	>1 KW	0
22. Production Feasibility	Easily produced	5	No theoretical limitation	1	Power considerations affect feasibility	2
23. Design Complexity	Low complexity Few parts	5	Moderate	2	Moderate	3
24. Production Cost	Low cost (50K)	5	75 K	3	50 K	4
		TOTAL POINTS		25		52
			FINAL AVERAGE		39	

EVALUATION FORM #1

Display Technique D.C.PLASMA

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	50	0	100	5
2. Spot Size	5 mils	3	8 mils	2	5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	100x100 elements	1	9.5 inches 10^6 elements	4
4. Brightness	1300 FL minimum	7	10 FL	-7	100 FL	-7
5. Uniformity	± 10%	5	±12%	4	±10%	5
6. Contrast Ratio	23 - 1	2	23 - 1	2	23 - 1	2
7. Gray Scale	10 shades of gray	8	6	0	6	0
8. Color	2 or more colors	1	2	1	2	1
9. Scanning Rate	20 MHz	12	5 MHz	3	20 MHz	12
10. Storage	2 minutes	1	No	0	No	0
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	1000 hours	2	1000 hours	2
12. Maintainability	1000 hours between adjustments	5	400 hours	2	600 hours	3

EVALUATION FORM #2

Display Technique D.C.PLASMA

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards		Can be ruggedized	
13. Temperature and Humidity	Meets MIL-E-5400	2	No	0	Yes	2
14. Shock	Meets MIL-E-5400	2	No	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	1.5 Ft^3	2	1 Ft^3	3
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	100 pounds	1.3	75 pounds	2.2
20. Average Power Consumption	<100 watts	3	6 KW	-3	4 KW	-3
21. Peak Power Consumption	<1 KW	1	10 KW	0	10 KW	0
22. Production Feasibility	Easily produced	5		4		4
23. Design Complexity	Low complexity Few parts	5		4		4
24. Production Cost	Low cost (50%)	5	50 K	4	50K	4
			TOTAL POINTS	23		53
			FINAL AVERAGE		38	

EVALUATION FORM #1

Display Technique IBM DEFORMOGRAPHIC STORAGE DISPLAY TUBE

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	330	5	480	5
2. Spot Size	5 mils	3	3 - 4 mils	3	1 - 2 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	3 in. to 10 ft.	4	4 in. to 10 ft.	4
4. Brightness	1300 FL minimum	7	Source Dependent 1700 FL (3"x3")	4.2	Source Dependent 1700 FL(10"x10")	4.2
5. Uniformity	± 10%	5	Est. ±24%	-2	Est. ±12%	4
6. Contrast Ratio	23 - 1	2	30 - 1 minimum	2	10 - 1	.8
7. Gray Scale	10 shades of gray	8	10	8	5	2
8. Color	2 or more colors	1	2	1	3	1
9. Scanning Rate	20 MHz	12	2.8 MHz	1.7	20 MHz	12
10. Storage	2 minutes	1	30 minutes	1	>30 minutes	1
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	<100 hours	-12	400 hours	-10
12. Maintainability	1000 hours between adjustments	5	<100 hours	0	200 hours	1

EVALUATION FORM #2

Display Technique IBM DEFORMOGRAPHIC STORAGE DISPLAY TUBE

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet standards		Can be ruggedized	
13. Temperature and Humidity	Meets MIL-E-5400	2	Room temperature	0	-55 - 50°C	1
14. Shock	Meets MIL-E-5400	2	No	0	With difficulty	1
15. Vibration	Meets MIL-E-5400	2	No	0	With difficulty	1
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	~4.5 Ft^3	-4	~2 Ft^3	1
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	75 pounds	2.2	40 pounds	3
20. Average Power Consumption	<100 watts	3	Tube - 8 watts Light - 150 watts	2.5	Tube - 8 watts Light - 150 watts	2.5
21. Peak Power Consumption	<1 KW	1	<1 KW	1	<1 KW	1
22. Production Feasibility	Easily produced	5	High Risk	1	Low to moderate	2
23. Design Complexity	Low complexity Few parts	5	Moderate to high	2	Moderate to high	2
24. Production Cost	Low cost (50K)	5	75K	[illegible]	50K	4

TOTAL POINTS 25 50

FINAL AVERAGE 37

EVALUATION FORM #1

Display Technique CATHODOCHROMIC

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
1. Resolution	100 dots/inch	5	100	5	Depends on elec. beam size	5
2. Spot Size	5 mils	3	5 mils	3	5 mils	3
3. Screen Size	9.5 in. square 8.93×10^5 elements	4	5 inches	2	10 inches	4
4. Brightness	1300 FL minimum	7	Source Dependent ~1700 FL	4.2	Source Dependent ~1700 FL	4.2
5. Uniformity	± 10%	5	Decreases rapidly Est. ±28%	-4	Est. ±16%	2
6. Contrast Ratio	23 - 1	2	10 - 1	0.8	10 - 1	0.8
7. Gray Scale	10 shades of gray	8	7	2	7	2
8. Color	2 or more colors	1	1	0	2	1
9. Scanning Rate	20 MHz	12	4 KHz	0	5 MHz	3
10. Storage	2 minutes	1	Months	1	Months	1
11. Reliability MTBF	2000 hours system 5000 hours disp. and elec.	12	< 300 hours	-12	1000 hours	2
12. Maintainability	1000 hours between adjustments	5	< 200 hours	1	600 hours	3

EVALUATION FORM #2

Display Technique CATHODOCHROMIC

Display Characteristics	VDS Design Goal	Weighting Factor	Present Performance Levels	Weighting Factor	1975 Future Performance Levels	Weighting Factor
Ruggedness and Environmental Limitations (Items 12 - 15)	Ruggedness meets MIL-E-5400		Does not meet MIL Standards		Can be ruggedized	
13. Temperature and Humidity	Meets MIL-E-5400	2	No	0	Yes	2
14. Shock	Meets MIL-E-5400	2	No	0	Yes	2
15. Vibration	Meets MIL-E-5400	2	No	0	Yes	2
16. EMI and RFI	Meets MIL STD 456	2	No	0	Yes	2
17. Volume	<1.5 Ft^3	4	2 Ft^3	1	1.5 Ft^3	2
18. Form Factor	Two or more packages	1	2 packages	1	2 packages	1
19. Weight	<100 pounds	3	50 pounds	3	50 pounds	3
20. Average Power Consumption	<100 watts	3	1 KW (Heater - 1200W)	-3	1 KW	-3
21. Peak Power Consumption	<1 KW	1	>1 KW	0	>1 KW	0
22. Production Feasibility	Easily produced	5	Moderate	3	Moderate	3
23. Design Complexity	Low complexity Few parts	5	Moderate	3	Moderate	3
24. Production Cost	Low cost (50K)	5	50 K	4	25 K	5

TOTAL POINTS 15 53

FINAL AVERAGE 34

APPENDIX A3

THE DIGISPLAY FLAT PANEL DISPLAY TUBE

The DIGISPLAY is a unique, flat panel, digitally addressed electron beam display which has been developed by Northrop for military and commercial applications. Its uniqueness is illustrated in figure 77 where it is pictorially compared with a conventional CRT. The DIGISPLAY utilizes an areal electron source followed by a series of very thin, apertured, control plates which are aligned and act collectively to generate a scanning electron beam. The instantaneous position of the beam is determined by digital addressing signals applied to patterned electrodes on the control plates. By switching the plate voltages sequentially, an electron beam scanning pattern is achieved. Inherent features of the DIGISPLAY, which are in sharp contrast with a conventional CRT, include flat configuration, digital address, and fixed linearity and registration.

Other important advantages of the DIGISPLAY include multiple beam and pseudorandom scanning capability. Multiple beam scanning can be used to increase beam dwell time and thereby achieve high screen brightness at reduced input power levels. Pseudorandom scan allows a reduction in frame rate without the presence of noticeable flicker. It can also provide spatial coding (scrambling) for secure information transmission without an increase in bandwidth. In addition, the digital nature of the DIGISPLAY permits handling of input signals directly from digital equipment such as computers, data processors, magnetic recorders, data links, and memory units, with a minimum of interface equipment.

A storage DIGISPLAY, which is similar to a direct view storage tube, will be emphasized for the VDS system. The primary advantage of a storage DIGISPLAY over its nonstorage counterpart is a dramatic increase in display brightness capability. High brightness capability is of considerable importance to the VDS display subsystem because of the high probability that the display will be viewed under high ambient illumination conditions.

Addition of storage to the DIGISPLAY is inherently much simpler than the addition of storage to the CRT. Figure 78 illustrates the mesh storage CRT and the mesh storage DIGISPLAY design configurations. The direct view storage

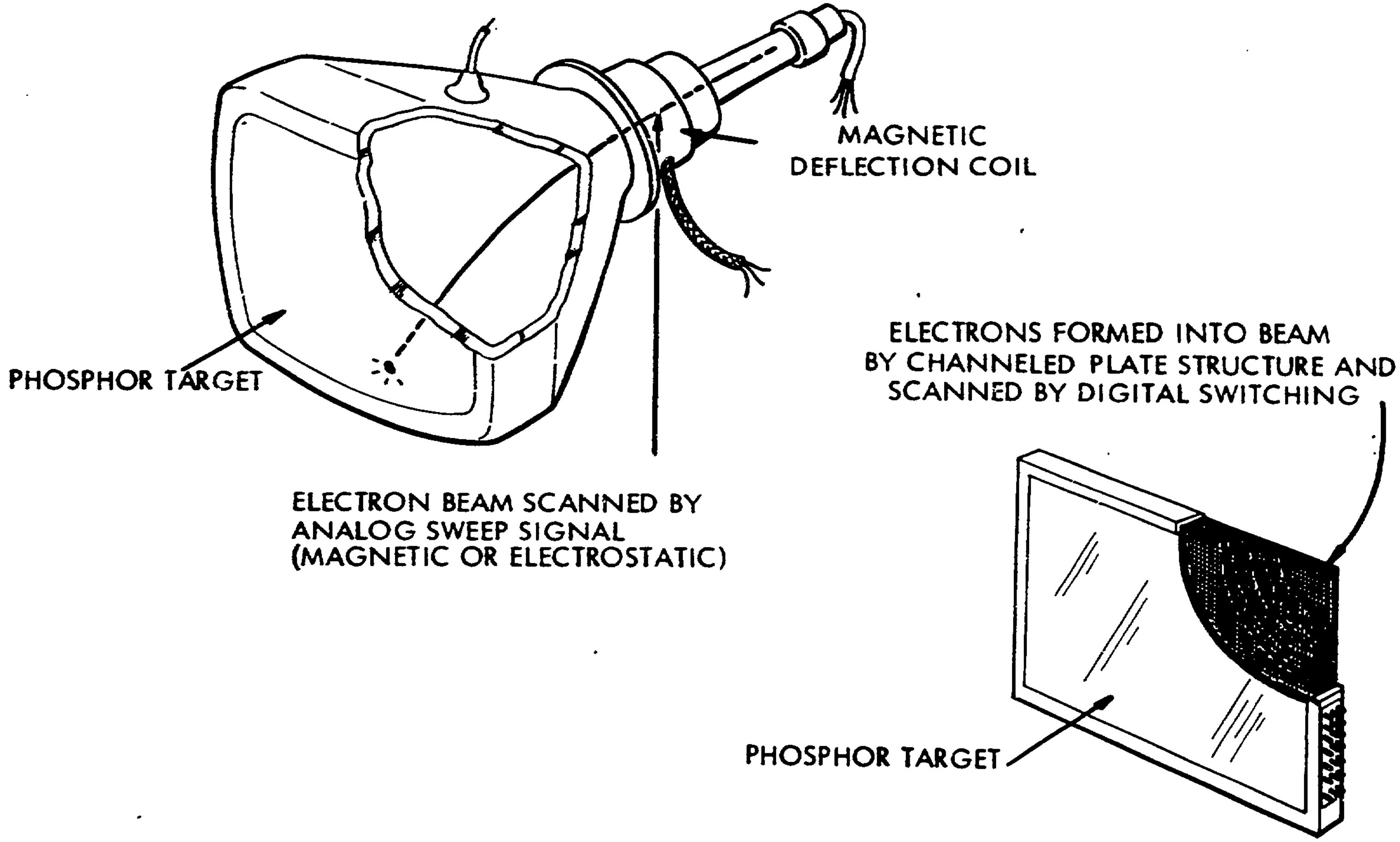
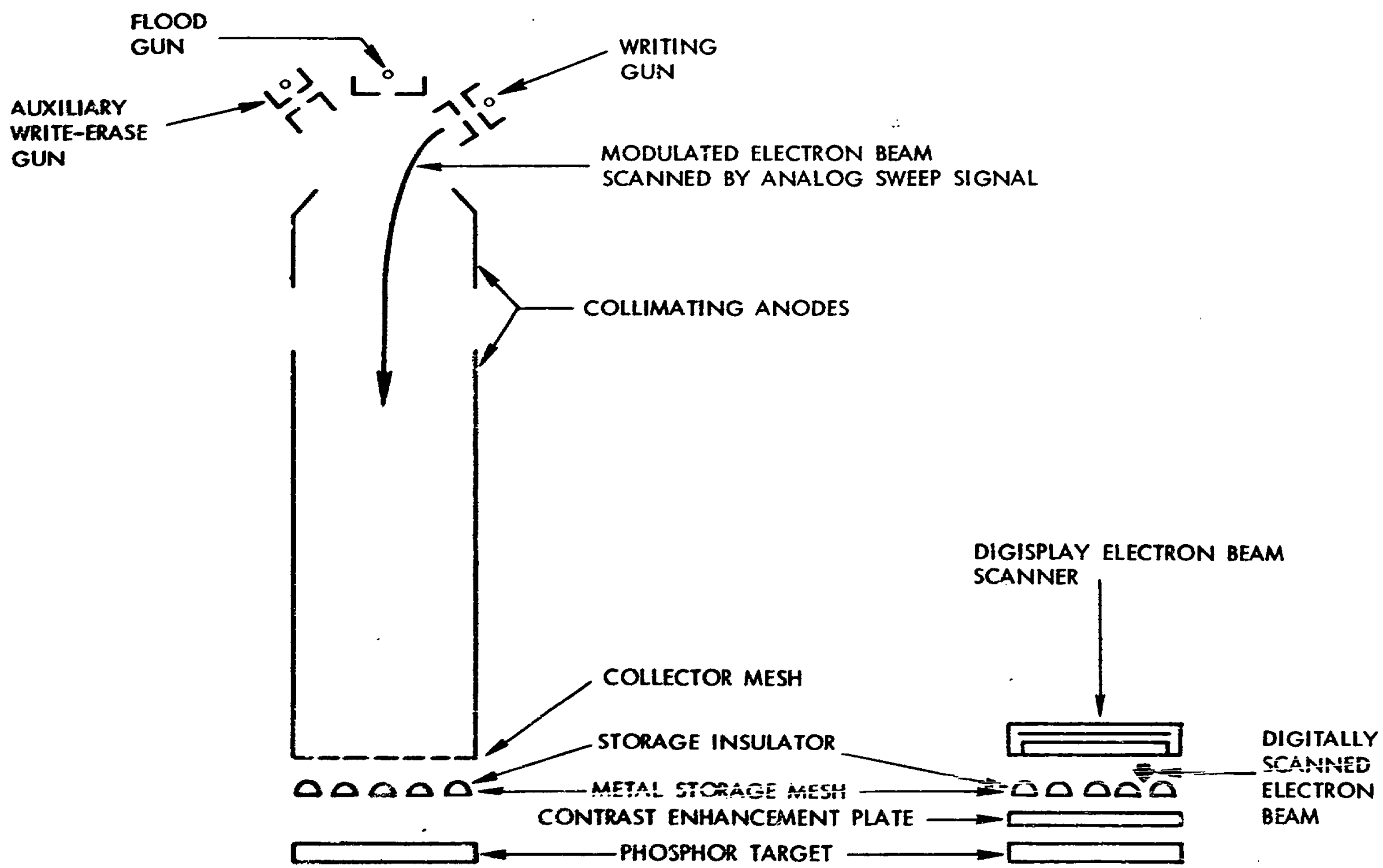


FIGURE 77 DIGISPLAY COMPARED WITH CONVENTIONAL ELECTRON BEAM SCANNING



A. CONVENTIONAL DIRECT VIEW STORAGE CRT

B. MESH STORAGE DIGISPLAY

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FIGURE 78 STORAGE CRT AND STORAGE DIGISPLAY CONFIGURATIONS

CRT configuration requires several electron guns, a much larger envelope, and a complex collimating system. In contrast, the storage DIGISPLAY does not require additional guns, a complex collimating system, or a significantly larger envelope.

DIGISPLAY PRINCIPLES OF OPERATION

The digital electron beam scan is unique to Northrop's DIGISPLAY and is responsible for many of its advantages over other display techniques. The digital scan is accomplished by a series of thin, electroded control plates to which digital addressing signals are applied. Figure 79 is an exploded view of a simplified DIGISPLAY having only 64 resolution elements and showing the location of the control plates relative to the other essential components. For descriptive simplicity the DIGISPLAY illustrated in figure 79 is electroded with half-splitting (2 leads per plate) binary patterns, and is shown only to permit the explanation of the DIGISPLAY operating concepts in simplest terms. In actual working displays, however, multilead electroding patterns are used to combine the function of several of the plates shown in the figure, so that fewer plates are required for complete decoding.

The operation of the simplified DIGISPLAY of figure 79 is as follows. Electrons travel from the areal cathode through a series of apertured plates (decoding plates and modulation plate) to the phosphor target. Each plate is constructed from an inexpensive glass substrate and contains an array of channels through which the electrons flow. The front and back surfaces of each plate are coated with conductive electrode patterns which connect groups of channels according to a predetermined coding scheme. These plates act collectively to cut off electron flow so that single or multiple electron beams emerge from the last plate at discrete positions determined by the digital addressing signals applied and the actual electrode coding utilized. The scanning beam or beams then write information on a phosphor (or storage) target whereupon it can be viewed through the faceplate.

Potentials are applied to the electrodes of each plate such that half the channels have an electron accelerating potential and half have an electron retarding potential. In the first decoding plate, the 32 channels in the

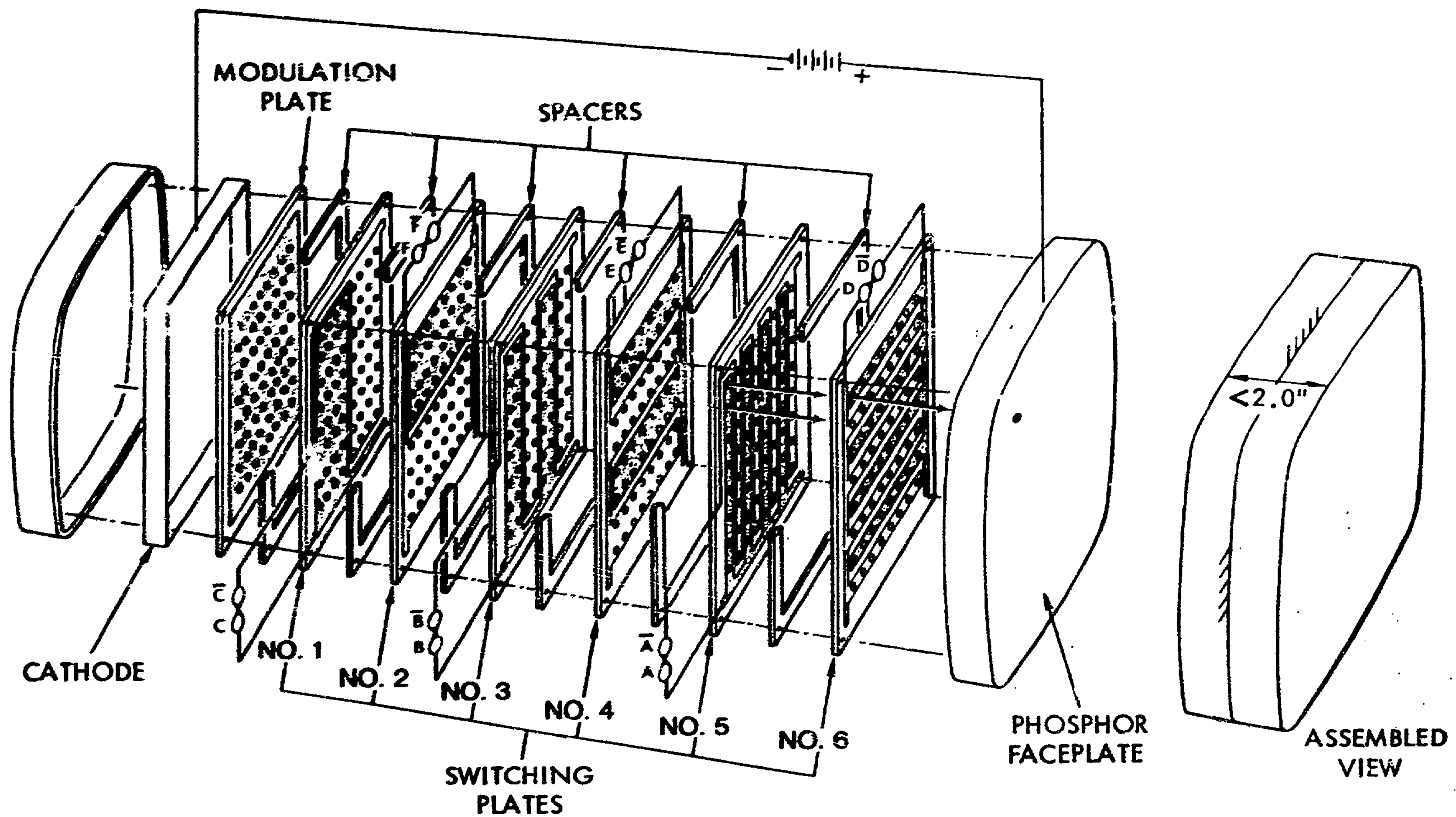


FIGURE 79 EXPLODED VIEW OF 8x8 ELEMENT DIGISPLAY WITH TWO-LEAD BINARY ELECTRODING

left half of the plate have a positive potential applied to them so the electrons come through; the 32 channels in the right half of the plate have a negative potential which causes the electron trajectories to reverse and thus produce beam cutoff. The electrode pattern on the second plate is identical to that of the first except for a 90° rotation. Electrons coming out of the 32 channels in the left half of the first plate enter the corresponding channels in the second plate. Since the channels in the lower half of this plate are biased off, electrons emerge only from the 16 channels in the upper left quadrant and proceed to the third plate. In the third plate, the eight channels in the right half of the quadrant are biased off so that the electron flow is bisected down to eight elements "on." As can be seen in figure 79, this selective bisection process continues in the following plates until only a single beam emerges from the final plate - in this case, in the upper left corner. The position of this beam can be changed simply by reversing the polarity of the potential on one or more plates with an electronic switch.

To illustrate, suppose one wants the beam to scan in a linear raster mode. Starting with the plate potentials as shown in figure 79, the flip-flop circuit driving plate No. 5 would be switched, causing the two electron beams emerging from this plate to move from the first column of channels to the second. The lower electron beam is stopped, as before, in the last plate and the emerging beam moves one position to the right. To switch the beam another position to the right, plate No. 3 and plate No. 5 are switched simultaneously. Continued switching of the appropriate plates will cause the beam to scan out the entire frame in a linear raster mode. It should be noted that the beam can be made to scan in a nonlinear or pseudorandom mode just as easily as a linear mode by changing the plate switching sequence.

Conventional CRT displays normally contain only a single electron gun and therefore have only a single electron beam for writing the information on the phosphor. The DIGISPLAY, however, can have as many electron beams as there are channel holes in each plate (and this limit is actually approached in storage DIGISPLAY operation). In a single beam DIGISPLAY, all but the one desired beam are cut off by the decoding plates. In figure 80, a 4-beam scanning mode is illustrated. Plates No. 1 and 2, as shown in figure 79, have been removed. The modulation plate is segmented into four quadrants so

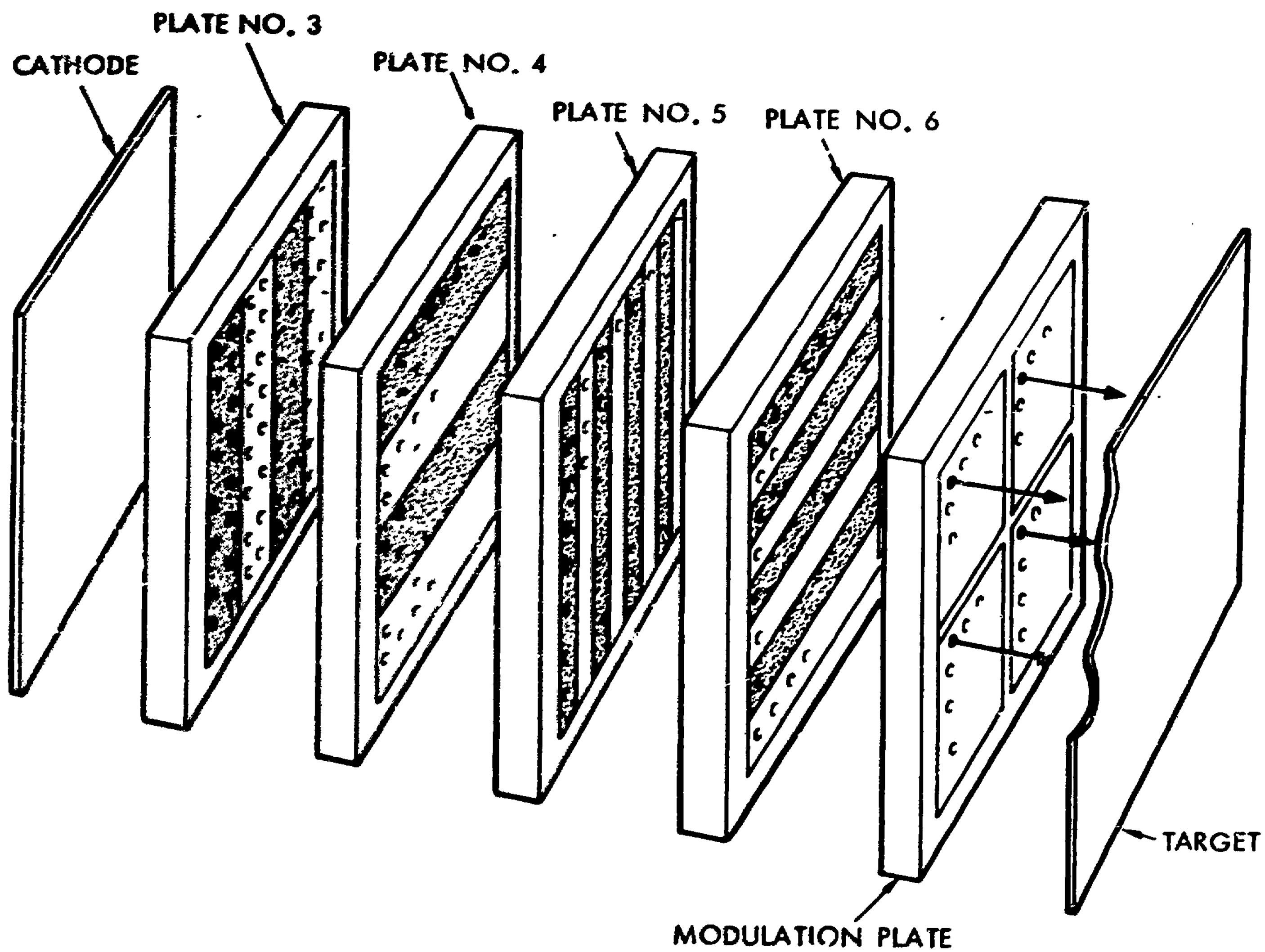


FIGURE 80 MULTIPLE (FOUR) BEAM SCANNING MODE

that separate video information can be written by each beam. Note that for a given frame rate, the dwell time of each scanning beam is four times longer in a 4-beam scanner than in a single beam scanner, thus bombarding each phosphor element with four times as many electrons per frame, leading to a corresponding increase in display brightness.

The DIGISPLAY shown in figure 79, for reasons of simplicity, has binary half-splitting decoding plates. It has been found in actual practice, however, that other decoding schemes are more efficient than the simple two leads per plate technique shown in the figure. These decoding schemes involve the "combining" of two or more decoding patterns on one plate. However, as plates are "combined," the total number of leads will generally increase. The advantage of the reduction of the number of plates must therefore be compared with the added complexity of additional leads and switching circuitry to obtain an optimum configuration. It should also be noted that as more plates are combined, the areas of the individual switching elements are reduced, thereby reducing the capacitive load and hence switching power, and also increasing the maximum possible beam stepping rate. It may be readily seen that for large displays consisting of many resolution elements (channel holes), the multileading technique becomes very beneficial. A number of DIGISPLAYs have been designed, fabricated, and tested using this principle. For example, a 512x512 DIGISPLAY has recently been successfully demonstrated using only four plates (three decoding and one modulation).

THE STORAGE DIGISPLAY

In any self-luminous, scanned display, such as the CRT, the brightness of the display is inversely proportional to its size, all other parameters being held constant. This decrease in brightness with increasing display size is due either to a decrease in scanning spot density or to a decrease in spot dwell time. With most CRT displays only three alternatives are available to alleviate this low brightness situation: an increase of the scanning beam current density, an increase of the phosphor potential, or the incorporation of a direct-view storage target. With the DIGISPLAY the first alternative is extremely unattractive because of the penalties incurred as a result of its

large-area flood gun. The second alternative is only slightly attractive because only a moderate increase in brightness can be expected without running into difficulties incurred by excessively high phosphor potentials. Fortunately, however, the DIGISPLAY is especially well suited to direct-view storage since a necessary component of a storage display, the flood gun, is inherent to the DIGISPLAY configuration. Furthermore, direct-view storage affords orders of magnitude increases in display brightness due to the effectively long dwell times resulting from flood operation. Preliminary experiments with storage in DIGISPLAY have verified this fact.

Storage is very difficult and expensive to implement in a CRT because of the problems of maintaining linearity and good focus of the writing gun while at the same time adding a flood gun which operates in a defocused condition. In contrast, storage is relatively easy to implement in the DIGISPLAY as illustrated by figure 81. In addition to the usual nonstorage DIGISPLAY components, a storage DIGISPLAY requires the inclusion of only a collector plate, a storage target, and a contrast enhancement plate (optional). Both the collector and contrast enhancement plates are similar to the decoding plates with the one exception that they have no decoding conductor pattern. Consequently the entire stack, from the input buffer to the constrast enhancement plate, is typically 0.100 - to 0.150-inch thick. The storage target itself is merely a metal mesh coated on the electron input side with a dielectric material having good secondary electron emission (SEE) characteristics (yield of unity at 40 volts and yield of 2 - 3 at several hundred volts of primary energy). Simple experiments have indicated that the storage mesh itself may possibly be replaced by a modified aperture plate coated with SEE material.

The actual method of storage DIGISPLAY operation is discussed below for each of the three required modes - erase, write, and flood.

1) <u>Erase</u> - The decoding plates are operated in the "all holes ON" condition with between 0 and 40 volts accelerating potential on the metal storage mesh. The SEE yield is then less than unity, and the surface of the dielectric material on the mesh is charged negative, erasing any information (positive charge) previously written on the mesh. Typical erase times are approximately 100 times the write time. During the erase time,

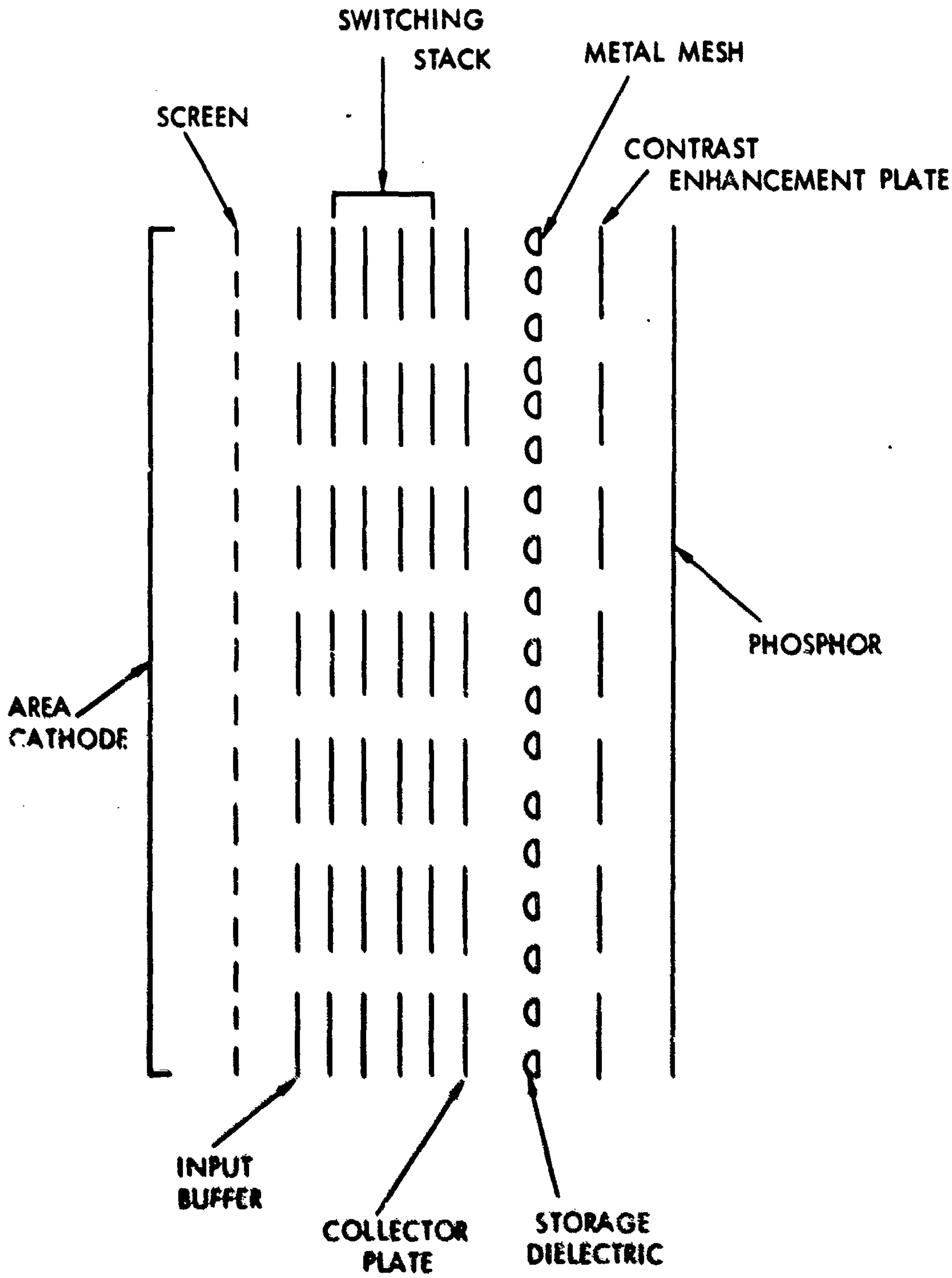


FIGURE 81 TYPICAL STORAGE DIGISPLAY CONFIGURATION (EXPLODED VIEW)

the contrast enhancement plate is biased below cathode potential to prevent the electron beams from striking the phosphor, thus preventing loss of contrast caused by illuminating the phosphor with the erase beams.

2) Write - In the write time interval, the decoding plates are scanned through one frame (or one-half frame when interlaced) of information in the same manner as in a nonstorage DIGISPLAY, including modulation to provide gray scale. The metal backing mesh of the storage target is elevated to several hundred volts above cathode potential, so that the scanned and modulated electron beams striking the dielectric layer cause it to charge positive due to the SEE ratio of > 1. The secondary electrons generated in writing the information on the storage dielectric material are absorbed on the collector plate, which is held at a potential somewhat above that of the mesh itself. The amount of positive charge thus written on the dielectric surface, for each resolution element, is dependent on the incident beam current and the (write) time this current is allowed to strike the dielectric. Commercially available storage targets typically require a charge density of approximately 10^{-8} coulombs/square inch to write the target to 80% of full brightness.

3) Flood - With one frame of information written on the dielectric surface of the storage target, the decoding stack is again switched to "all holes ON", as in the erase mode. However, the metal backing mesh of the storage target is now set at or near cathode potential, such that:

a) Areas which are charged completely positive during the write cycle transmit electrons to the phosphor.

b) Areas which are not positively charged repel electrons back to the collector plate.

c) Areas which are charged less positive than in case (a) due to modulation during writing, transmit fewer electrons than in case (a) and retain the written gray scale.

The length of the flood cycle relative to the write cycle determines the brightness of the display. The maximum flood time possible is limited by the

length of time the stored charge will remain on the dielectric surface, and by the upper time required by system requirements. Storage times of as long as 15 minutes have been demonstrated.

The storage DIGISPLAY should have the following advantages over a direct view storage CRT:

a) An inherently simpler design with only one gun, no ion repeller, and no complex collimating system which should result in a lower manufacturing cost.

b) Much smaller in size, lighter in weight, and more rugged construction.

c) Storage time should be inherently longer since ion bombardment should be minimized by the presence of scanning plates.

d) Selective write and erase should be easier to implement.

e) Uniformity and registration are not hampered by off-axis guns.

f) Very fast erase.

g) No screen "flash" during erase, resulting in higher contrast.

h) Plus all the normal advantages of a DIGISPLAY over a CRT, which include:

- Superior registration because the electron beams are physically confined by accurately placed channels in the scanning plates.
- Digital address signal which is directly compatible with a computer interface, resulting in considerable savings in addressing circuitry.
- Random scan capability - unlike the CRT, the time required to switch the beam position in the DIGISPLAY is virtually independent of the distance the beam is moved.
- Flat panel construction - the total depth of the DIGISPLAY is approximately 2 inches.
- Stray-field independence - DIGISPLAY performance is relatively unaffected by stray electric and magnetic fields.

- Multibeam feature - the multibeam feature of the DIGISPLAY offers several advantages over the conventional writing techniques utilizing only a single beam and is much easier and less expensive to implement than in a CRT. Greater display brightness can be achieved with multiple beam scanning.

APPENDIX A4

LEAD CAPACITANCE DUE TO INTER-PLATE GAP SPACING

One of the three major contributors to the lead capacitance of DIGISPLAY decoding or modulator plates is the inter-plate gap capacitance resulting from the presence of adjacent plates on either side of the plate under consideration. The situation is illustrated in figure 82, which shows two DIGISPLAY plates in cross-section and separated by a spacer of thickness X_s and mean dielectric constant K_s. The inter-plate gap capacitance is then defined as the cumulative sum of the capacitances between a single thin-film conductor finger of width A, the two co-planar thin-film conductors spaced to either side by gaps of width G, and the single thin-film conductor on the adjacent plate.

In determining only the inter-plate gap component of the lead capacitance we will assume in this appendix that the electric field displacement is totally confined to the inter-plate spacer region of mean dielectric constant K_s. This assumption readily leads to a solution such as given by Wolfe* as his case 9. Following Wolfe we have that the inter-plate gap capacitance per unit length is

$$\frac{C_s}{\ell} = 2K_s \epsilon_0 \frac{K(k)}{K(k')}$$

where K(k) is the complete elliptic integral of the first kind for modulus k. The moduli k and k' are (again following Wolfe)

$$k = \frac{\tanh\left[\frac{\pi A}{4X_s}\right]}{\tanh\left[\frac{\pi(A + 2G)}{4X_s}\right]}$$

$$k' = \sqrt{1 - k^2}$$

The inter-plate gap capacitance itself is then obtained from the product of the above equation and the effective length of the thin-film conductor finger under consideration. If S is the distance between adjacent holes in a DIGISPLAY plate and if the finger is K_L holes long, then this capacitance is

$$C_s = 2 K_s \epsilon_0 \frac{K(k)}{K(k')} \quad (SK_L)$$

where the moduli k and k' are as before.

*Wolfe, P.N., "Capacitance Calculations for Several Simple Two-Dimensional Geometries," Proceedings of the IRE, October 1962.

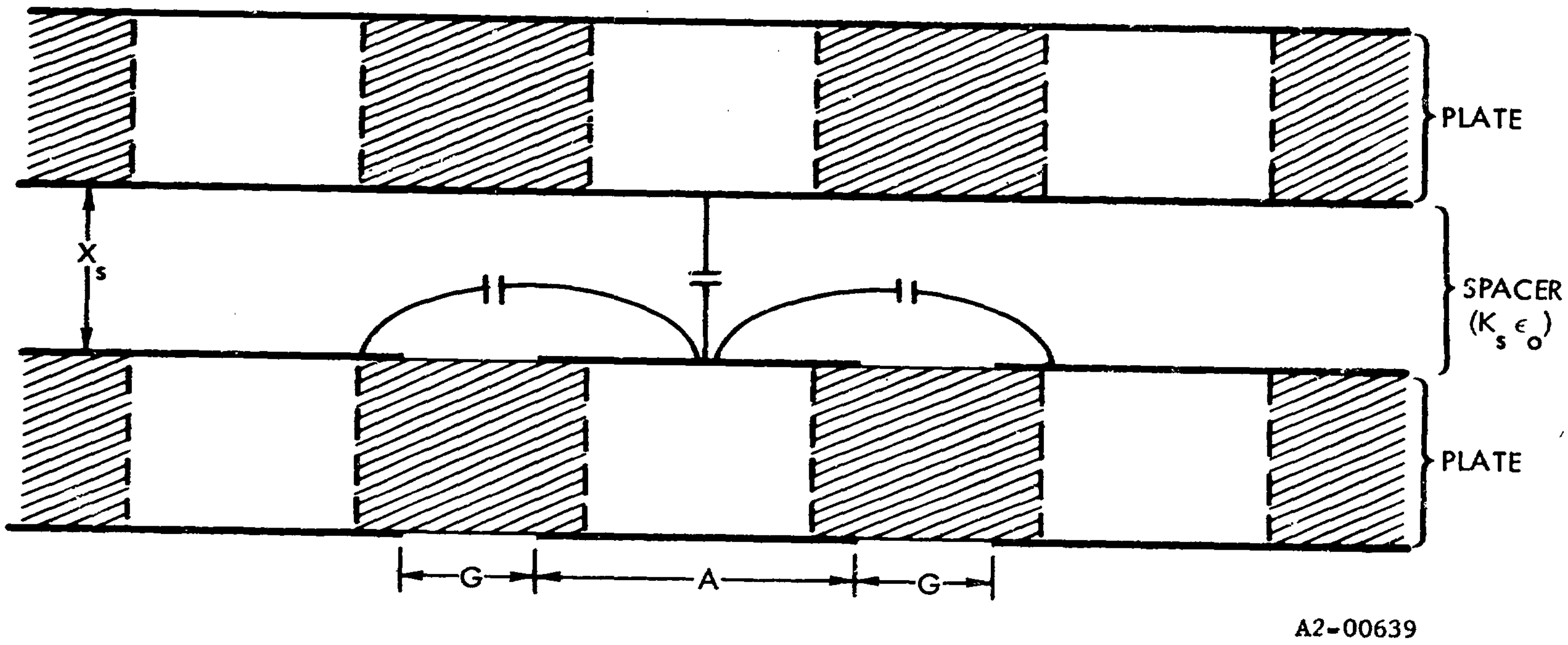


FIGURE 82 INTER-PLATE CAPACITANCE GEOMETRY

APPENDIX A5

LEAD CAPACITANCE DUE TO INTRA-PLATE GAP SPACING

Another of the three major contributors to the lead capacitance of DIGISPLAY decoding or modulator plates is the intra-plate gap capacitance resulting from the presence of thin-film conductors on both sides of the plate. Note that the intra-plate gap capacitance is internal to the plate under consideration and should not be confused with the inter-plate gap capacitance (see Appendix A4) which is external. Figure 83 illustrates the situation. A is the width of the thin-film conductor finger and G is the width of the gaps between this finger and its coplanar neighbors as in Appendix A4. The thickness of the plate is X_p and its dielectric constant is K_p.

We will assume this time that the electric field displacement is totally confined to the plate dielectric itself so as to avoid any interaction with the inter-plate gap capacitance determined in Appendix A4. Also, because each conductor on the upper surface of the plate is electrically connected to its corresponding conductor on the lower, we have that the normal derivative of the potential vanishes along the plate's horizontal center-line (a Neumann boundary) shown in figure 83. Hence, the problem can be divided in half to give the geometry shown in figure 84a. The problem can be further divided if we assume that the potential on the right-hand conductor is the same as that on the left. Then by symmetry we have an equipotential (a Dirichlet boundary) down the plate's vertical center-line yielding the geometry shown in figure 84b.

The capacitance of a similar although not identical geometry has been analyzed by Wolfe*. Wolfe's geometry (case 7) is illustrated in figure 85a and has the solution

$$\frac{C_7}{\ell} = \frac{1}{2} K_p \epsilon_0 \frac{K(k')}{K(k)}$$

where K(k) is the complete elliptic integral of the first kind for modulus k and the moduli are

*Wolfe, P.N., "Capacitance Calculations for Several Simple Two-Dimensional Geometries," Proceedings of the IRE, October 1962.

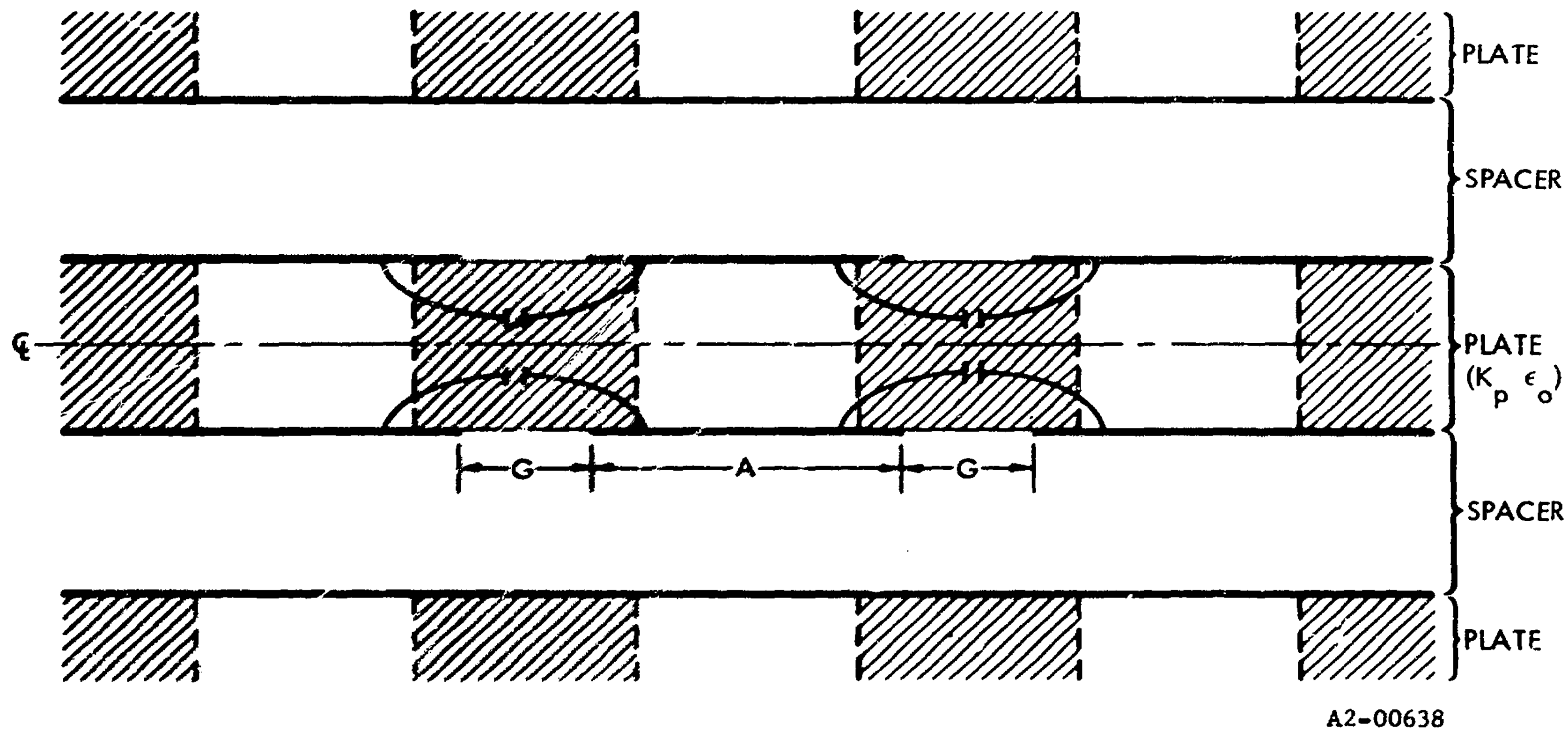
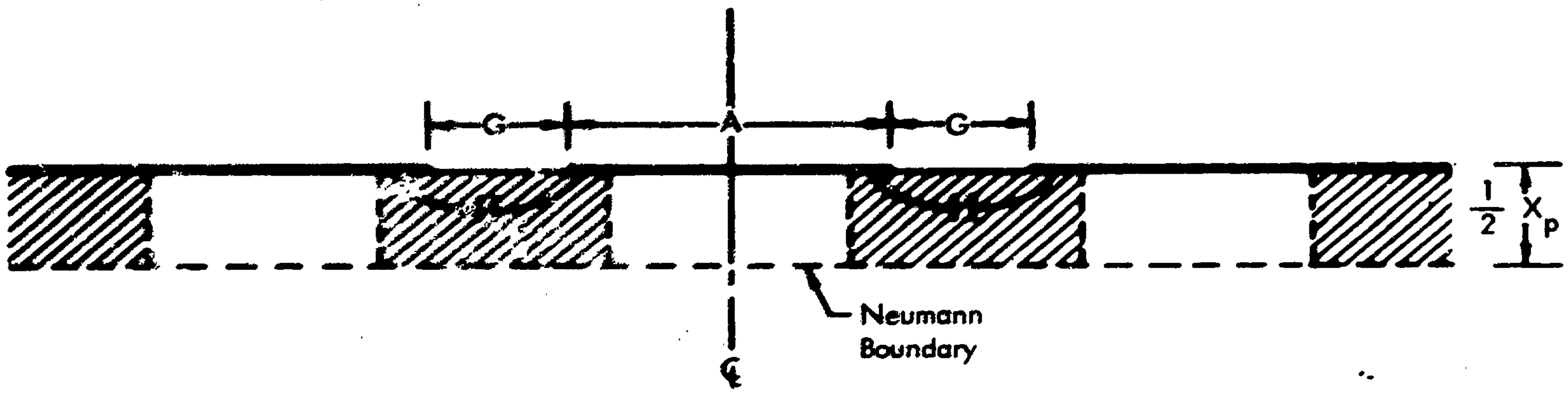
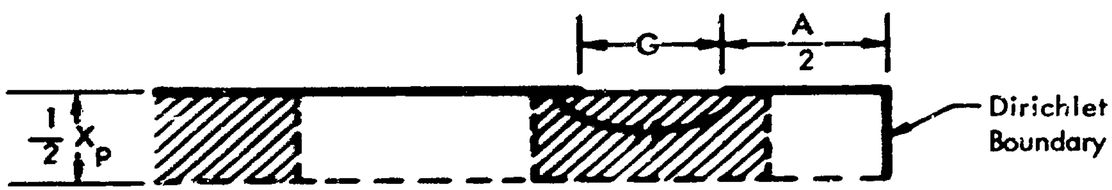


FIGURE 83 INTRA-PLATE CAPACITANCE GEOMETRY



a) Simplification Resulting from Neumann Boundary



b) Simplification Resulting from Dirichlet Boundary

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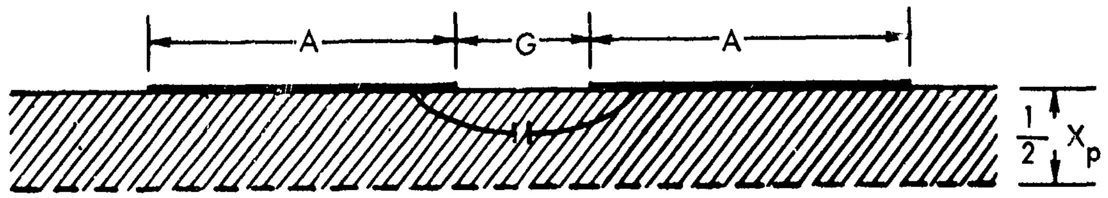
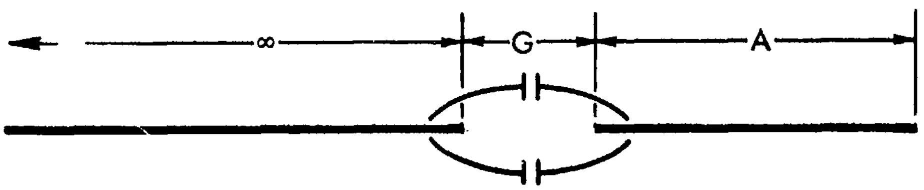
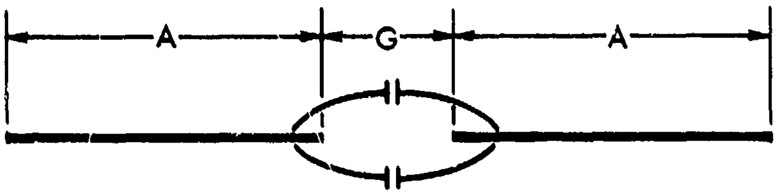
FIGURE 84 SIMPLIFIED GEOMETRIES WHICH ARE EQUIVALENT TO FIGURE 83



a) Wolfe's Case 7 Geometry



b) Two Coplanar Strips - One Infinite



c) Two Coplanar Strips - Both Finite

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FIGURE 85 GEOMETRIES FOR WHICH SOLUTIONS HAVE BEEN PUBLISHED

$$k = \frac{\tanh\left[\frac{\pi G}{2X_p}\right]}{\tanh\left[\frac{\pi(2A+G)}{2X_p}\right]}$$

$$k' = \sqrt{1 - k^2}$$

Note that the main difference between Wolfe's geometry and the geometry of figure 84b is the presence of the right angle bend in the center conductor and the considerably wider extent of the other. Since it is not known how to account for the bend, the bend's presence will be ignored by assuming that the center conductor is unbent and of width A as before. This obviously is an approximation to the actual case.

The effect of the wider left-hand conductor can be treated, however, if we employ a little sleight of hand. The solution for two coplanar but isolated strips, one of width A and the other infinite, as shown in figure 85b is known*

$$\frac{C_{infinite}}{\ell} = 2\,\epsilon_0\,\frac{K(k')}{K(k)}$$

where the moduli are now

$$k = \left(\frac{G}{A+G}\right)^{1/2}$$

$$k' = \sqrt{1 - k^2}$$

From the same source we also have that the capacitance per unit length between two finite strips of width A (see figure 85c) is

$$\frac{C_{finite}}{\ell} = \epsilon_0\,\frac{K(k')}{K(k)}$$

where the moduli are now

$$k = \left(\frac{G}{2A+G}\right)$$

$$k' = \sqrt{1 + k^2}$$

*See the American Institute of Physics Handbook.

Note that Wolfe's case 7 solution converges to this last solution if K is assumed to be unity and X_p is made infinite as it should.

By analogy then the approximate solution to the simplified geometry of figure 84b would be

$$\frac{C_p}{\ell} = K_p \epsilon_o \frac{K(k')}{K(k)}$$

where the new moduli are

$$k = \frac{\tanh\left[\frac{\pi G}{2X_p}\right]^{1/2}}{\tanh\left[\frac{\pi (A+G)}{2X_p}\right]^{1/2}}$$

$$k' = \sqrt{1 - k^2}$$

The intra-plate gap capacitance itself is then obtained from the product of the above equation and the effective length of the thin-film conductor finger under consideration. With S the distance between adjacent holes in a DIGISPLAY plate and K_L the length of the finger in terms of number of holes, the intra-plate gap capacitance is

$$C_p = K_p \epsilon_o \frac{K(k')}{K(k)} (SK_L)$$

where the moduli k and k' are as above.

APPENDIX A6

INTRA-PLATE HOLE CAPACITANCE

Each DIGISPLAY plate consists of an ordered two-dimensional array of approximately cylindrical holes. On one or both sides of each plate, vacuum deposited electrodes interconnect groups of these cylindrical holes such that electrical conditions conducive to electron multiplication gain may be imposed across one group while electrical conditions inhibitive to gain are imposed across the other. In switching the plate such that first one group of channel holes are ON and then the other, the capacitance between the two channel hole groups becomes of importance.

This capacitance may be analytically determined if a few reasonable approximations are allowed. For example, in the following analysis we shall consider only those channel holes immediately adjacent to a single straight electrode boundary. Furthermore, we shall consider these channel holes as being cylindrical in shape and infinite in length (i.e., end effects will be neglected). Hence, we shall determine the capacitance per unit length between two co-parallel linear arrays of cylinders.

An exact solution to this problem is quite difficult to obtain. However, similar problems can be found which have been previously solved by those with considerable expertise in handling electrostatic field situations. One such similar problem may be found in the text by Ramo, Whinnery, and Van Duzer.* In this text the interelectrode capacitances of a parallel plane triode are derived subject to a few basic assumptions. Although at least one of these assumptions will be found slightly invalid for our situation, we will ignore this fact since we have already made a somewhat questionable assumption in neglecting the end effects of finite-length cylinders. We will summarize this interelectrode capacitance analysis in the following paragraphs and will subsequently illustrate how this analysis can be applied to our particular problem.

Consider first the idealized triode with plane cathode, plane anode, and a grid of parallel wires as sketched in figure 86a. With the coordinates

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*Ramo, S., Whinnery, J. R., and Van Duzer, T., Fields and Waves in Communications Electronics, John Wiley and Sons, Inc., New York (1965) p. 318-321.

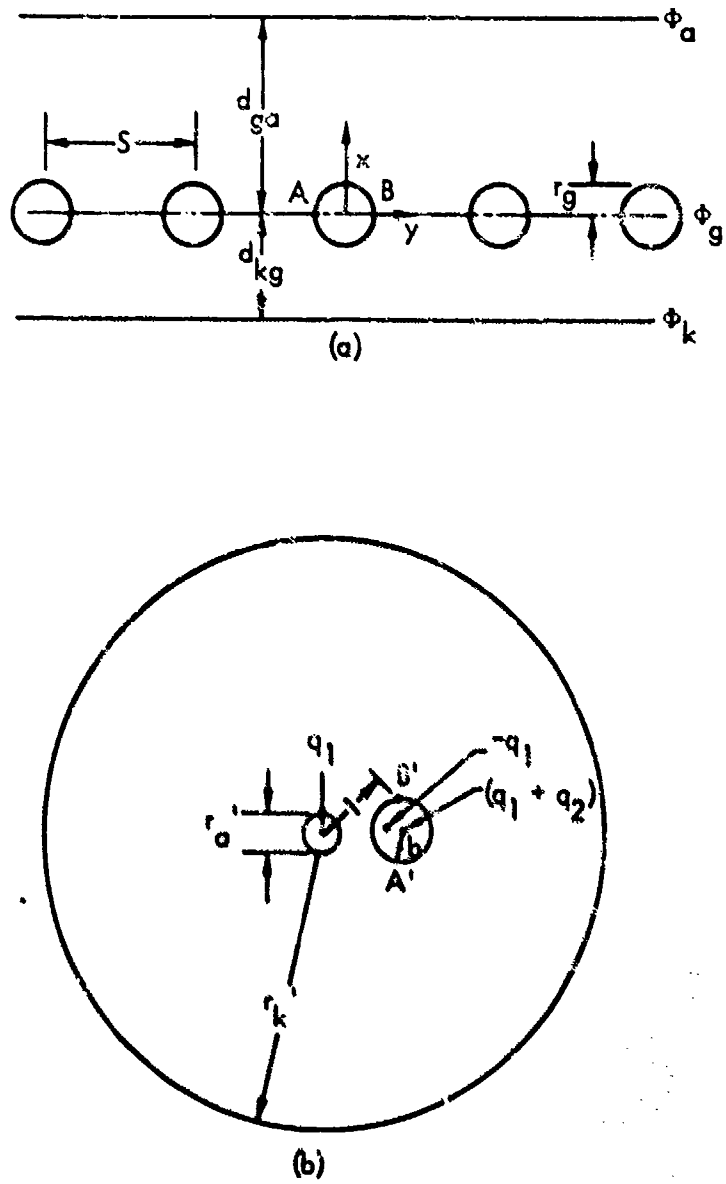

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FIGURE 86 PLANAR TRIODE WITH PARALLEL-WIRE GRIDS AND ITS TRANSFORMED FIGURE IN THE Z' PLANE

and dimensions as shown in this figure, this two-dimensional problem may be transformed to that of figure 86b by the complex function:

$$Z' = \exp\left(-\frac{2\pi Z}{S}\right) = \exp\left(-\frac{2\pi x}{S}\right)\exp\left(-j\frac{2\pi y}{S}\right)$$

This transformation bends the whole triode assembly about a point just outside of the anode such that each grid wire is bent around such that they all map into the same cylindrical shape whose center is located at $Z' = 1$. If we have N grid wires, the transformation will result in N geometries such as shown in figure 86b each mapped one on top of the other. In what follows we shall consider only one of these identical geometries.

In the transformed figure, the anode and cathode have become coaxial cylinders of radii r_a' and r_k', respectively, and each of the grid wires has transformed into a single nearly-circular cylindrical figure centered at $Z' = 1$. This transformed grid figure may be approximated well enough by a circle of radius b where

$$b = 2\sin\left(\frac{\pi r_g}{S}\right)$$

if it is assumed that the grid spacing S is at least five times the grid radius r_g. This assumption is generally very good for most grid structures in vacuum tubes, but is only fair in our case where the grid wires will represent channel holes which are typically spaced (center-to-center) at a distance only four times the channel radius.

The problem in the Z' plane may now be solved by utilizing a series of line images. Actually for typical triode dimensions, the grid-to-cathode distance d_{gk} and the grid-to-anode distance d_{ga} are large relative to the grid spacing S. If we assume that this is so, then the transformed cathode radius r_k' will be very large and the transformed anode radius r_a' will be very small, so that the transformed anode may be considered a line charge and a single imaging of this in the transformed grid cylinder may be sufficient. This image is at a distance b^2 from the center of the grid wire so that the three line charges of concern are now the anode charge q_1 at the origin, the image charge $-q_1$ at $Z' = 1 - b^2$ and the grid charge $q_1 + q_2$ at $Z' = 1$. (The choice of the last value is made so that the net charge on the grid wire is q_2.) The potential field produced by these three line charges is then

$$\phi = -\frac{1}{2\pi K\epsilon_0}\left[q_1 \ln r_1 - q_1 \ln r_2 + \left(q_1 + q_2\right)\ln r_3\right] + A$$

where K is the dielectric constant of the medium, r_1, r_2, and r_3 are the distances from the arbitrary point in space at which the potential is desired to the line charges q_1, $-q_1$, and $q_1 + q_2$, respectively, and A is an arbitrary constant dependent on the potential zero reference.

Since r_k' has been assumed to be large, the potential on the cathode may be approximated by letting

$$r_1 \approx r_2 \approx r_3 \approx r_k'$$

whereupon the cathode potential becomes

$$\phi_k = -\frac{1}{2\pi K\epsilon_0}\left(q_1 + q_2\right)\ln r_k' + A$$

Since the r_a' has been assumed to be small, the potential at the anode may be approximated by considering only the line charge q_1 on the axis whereupon the anode potential becomes

$$\phi_a = -\frac{1}{2\pi K\epsilon_0} q_1 \ln r_a' + A$$

The potential on the grid may now be found by choosing some point such as $Z' = 1 - b$ on the grid wire for evaluating the potential which yields

$$\phi_g = -\frac{1}{2\pi K\epsilon_0}\left[q_1 \ln (1-b) - q_2 \ln b\,(1-b) + (q_2 + q_1) \ln b\right] + A$$

$$= -\frac{1}{2\pi K\epsilon_0} q_2 \ln b + A$$

The constant A may be determined by considering any of the three electrodes, say the cathode, as the zero reference whereupon the three potentials become

$$\phi_k = 0$$

$$\phi_a = -\frac{1}{2\pi K\epsilon_0}\left[q_1 \ln\left(\frac{r_a'}{r_k'}\right) - q_2 \ln r_k'\right]$$

$$\phi_g = -\frac{1}{2\pi K\epsilon_0}\left[-q_1 \ln r_k' + q_2 \ln\left(\frac{b}{r_k'}\right)\right]$$

The last two potential equations can now be solved for the line charges q_1 and q_2 either by direct substitution or, as a more general approach, by matrix inversion methods. When this is done we have

$$q_1 = \frac{\phi_a \ln\left(\frac{r_k'}{b}\right) - \phi_g \ln\left(r_k'\right)}{\frac{1}{2\pi K\epsilon_0}\left\{\ln\left(\frac{r_k'}{r_a'}\right)\ln\left(\frac{r_k'}{b}\right) - \left[\ln\left(r_k'\right)\right]^2\right\}}$$

$$q_2 = \frac{-\phi_a \ln\left(r_k'\right) + \phi_g \ln\left(\frac{r_k'}{r_a'}\right)}{\frac{1}{2\pi K\epsilon_0}\left\{\ln\left(\frac{r_k'}{r_a'}\right)\ln\left(\frac{r_k'}{b}\right) - \left[\ln\left(r_k'\right)\right]^2\right\}}$$

Inverse transformation of this result back into the ? plane then yields a somewhat similar looking result

$$q_1 = \frac{\left[\frac{d_{kg}}{S} - \frac{1}{2\pi}\ln\left(2\sin\frac{\pi r_g}{S}\right)\right]\phi_a - \left(\frac{d_{kg}}{S}\right)\phi_g}{\frac{1}{K\epsilon_0}\left\{\frac{d_{ka}}{S}\left[\frac{d_{kg}}{S} - \frac{1}{2\pi}\ln\left(2\sin\frac{\pi r_g}{S}\right)\right] - \left(\frac{d_{kg}}{S}\right)^2\right\}}$$

$$q_2 = \frac{-\left(\frac{d_{kg}}{S}\right)\phi_a + \left(\frac{d_{ka}}{S}\right)\phi_g}{\frac{1}{K\epsilon_0}\left\{\frac{d_{ka}}{S}\left[\frac{d_{kg}}{S} - \frac{1}{2\pi}\ln\left(2\sin\frac{\pi r_g}{S}\right)\right] - \left(\frac{d_{kg}}{S}\right)^2\right\}}$$

Now if we consider an equivalent circuit of the triode consisting of three interconnected electrode capacitances, C_{ga}, C_{kg}, and C_{ka} and then write the expressions for the total charge on the anode, Nq_1 and the total charge on the grid, Nq_2 we obtain

$$\begin{aligned} Nq_1 &= C_{ka}\,\phi_a + C_{ga}\left(\phi_a - \phi_g\right) \\ &= \left(C_{ka} + C_{ga}\right)\phi_a + \left(-C_{ga}\right)\phi_g \\ Nq_2 &= C_{ga}\left(\phi_g - \phi_a\right) + C_{kg}\,\phi_g \\ &= \left(-C_{ga}\right)\phi_a + \left(C_{kg} + C_{ga}\right)\phi_g \end{aligned}$$

Equating like terms in these expressions with those in the previous expressions then results in equations for the equivalent interelectrode capacitances, i.e.,

$$C_{ka} = - \frac{N \frac{1}{2\pi} \ln\left(2 \sin \frac{\pi r_g}{S}\right)}{\frac{1}{K\epsilon_0}\left\{\frac{d_{ka}}{S}\left[\frac{d_{kg}}{S} - \frac{1}{2\pi}\ln\left(2 \sin \frac{\pi r_g}{S}\right)\right] - \left(\frac{d_{kg}}{S}\right)^2\right\}}$$

$$C_{kg} = \frac{N\left(\frac{d_{ga}}{S}\right)}{\frac{1}{K\epsilon_0}\left\{\frac{d_{ka}}{S}\left[\frac{d_{kg}}{S} - \frac{1}{2\pi}\ln\left(2 \sin \frac{\pi r_g}{S}\right)\right] - \left(\frac{d_{kg}}{S}\right)^2\right\}}$$

$$C_{ga} = \frac{N\left(\frac{d_{kg}}{S}\right)}{\frac{1}{K\epsilon_0}\left\{\frac{d_{ka}}{S}\left[\frac{d_{kg}}{S} - \frac{1}{2\pi}\ln\left(2 \sin \frac{\pi r_g}{S}\right)\right] - \left(\frac{d_{kg}}{S}\right)^2\right\}}$$

We now have analytical expressions for the three interelectrode capacitances (per unit length) of a parallel plane triode. To use these expressions to calculate the capacitance between two parallel linear arrays of cylinders, we shall now move the cathode electrode far away from both the grid and the anode such that both d_{ka} and d_{kg} approach infinity. Note that this is allowed under the assumptions previously stated. With the cathode at infinity, we now have the situation of a grid which is co-parallel with a planar conductor, exactly one-half of our two co-parallel linear arrays of cylinders problem since by symmetry we will have a planar equipotential (Dirichlet boundary) midway between the two arrays.

When we let both d_{kg} and d_{ka} approach infinity, our first two interelectrode capacitance equations, those for C_{ka} and C_{kg}, both go to zero as they intuitively should. The third equation, however, which gives the capacitance between the grid and the anode, becomes greatly simplified yielding

$$C_{ga} = \frac{NK\epsilon_0}{\frac{d_{ga}}{S} - \frac{1}{2\pi}\ln\left(2 \sin \frac{\pi r_g}{S}\right)}$$

The capacitance per unit length between two co-parallel linear arrays of cylinders can then be immediately written as

$$\frac{C}{\ell} = \frac{NK\epsilon_0}{\frac{d}{S} - \frac{1}{\pi} \ln\left(2 \sin \frac{\pi r}{S}\right)}$$

where N is the number of cylinders of radius r in each array, S is the cylinder lattice spacing, d is the array spacing, and K is the dielectric constant of the intervening medium.

In DIGISPLAY plates the lattice spacing S and the array spacing d are typically the same. When this is the case, the capacitance between the two arrays of holes can be written as

$$\frac{C_h}{\ell} = \frac{NK\epsilon_0}{1 - \frac{1}{\pi} \ln\left(2 \sin \frac{\pi r}{S}\right)} \qquad \text{for } d = S$$

If the length of each hole is X_p, the thickness of a plate, and if the number of holes along the edge of the thin-film conductor finger is $N = K_L$, then the intra-plate hole capacitance may be written as

$$C_h = \frac{K\epsilon_0}{1 - \frac{1}{\pi} \ln\left(2 \sin \frac{\pi D}{2S}\right)} \left(K_L X_p\right)$$

where $D = 2r$ is the diameter of each hole.

APPENDIX A7

PHOSPHOR LIFE CONSIDERATIONS IN HIGH BRIGHTNESS APPLICATIONS

In multiple-beam or particularly in direct view storage display tubes operating at high brightness levels, phosphor deterioration due to either thermal burn or electronic aging may be a significant consideration which must not be neglected. In such situations it is important to utilize a phosphor which is characterized by high resistance to both thermal burn and electronic aging as well as by high luminous efficiency. Table 47 lists a number of phosphors which are potential candidates for such a situation.

Thermal burn is a deterioration of a phosphor's conversion efficiency resulting from chemical changes produced by excessive heat. Most standard phosphors (those for which a P number has been assigned by JEDEC) exhibit an average resistance to thermal burn. According to Bell[1] the P15 and P31 phosphors are very resistant to thermal burn whereas the P12, P16, P19, P26, and P33 phosphors burn easily especially so for the P33. All of the other standard phosphors which include most of the high brightness phosphors listed in Table 13 are moderate in burn resistance.

The thermal burn ranking given by Bell is wholly qualitative. No reference has been found that would indicate the quantitative thermal burn resistance of various phosphors. One reference[2] indicated, however, that under dc excitation, most aluminized phosphors can withstand a power density of up to 0.6 watts/cm^2 with no evidence of thermal burn. At a power density of over 1.5 watts/cm^2 the phosphor screen and the aluminum backing were found to volatilize.

A second reference[3] indicates that peak power densities as high as 10^6 watts per square centimeter have been achieved in projection tubes operating at 50 KV accelerating potential. This is obviously a low duty cycle condition as opposed to the 100 percent duty cycle discussed above and no reference is made as to phosphor life or faceplate cooling, if any.

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[1] R. A. Bell, "Principles of Cathode Ray Tubes, Phosphors, and High-Speed Oscillography," Hewlett-Packard Application Note 115.

[2] A. Pfahnl, "Aging of Electronic Phosphors in Cathode Ray Tubes," Proc. 5th National Conf. on Tube Techniques (1961).

[3] P. Seats, "The Cathode Ray Tube - A Review of Current Technology and Future Trends," IEEE Trans. Electron Devices, Vol. ED-18, No. 9, September 1971.

TABLE 47

CHARACTERISTICS OF HIGH-BRIGHTNESS ALUMINIZED SETTLED PHOSPHOR SCREENS

PHOSPHOR COMPOSITION	P-NUMBER	FLOURESCENCE	PERSISTENCE (@10%)	ABSOLUTE EFFICIENCY (WATT/WATT EXCIT.) *	LUMINOUS EFFICIENCY (LUMENS/WATT EXCIT.) *	CURRENT SATURATION	THERMAL BURN	COULOMB RATING ($COULOMB/CM^2$)	REMARKS
Zn_2SiO_4:Mn	P1	Yellow-Green	24 ms (1)	0.06 (2)	31.2 (2)		Average (7)	104.0 (4)	
ZnSCdS:Cu	P2	Yellow-Green	75 μs (1)	0.07 (2)	32.2 (2)		Average (7)	11.9 (4)	
ZnS:Ag + ZnSCdS:Ag	P4	White	60 μs (1)	0.15 (2)	43.5 (2)		Average (7)	4.5 (4)	Conventional TV
CaO MgO SiO_2:Ti	P4	White						55.5 (4)	Projection B&W TV
ZnO BeO SiO_2:Mn	P4	White	12.5 ms (3)		26.4 (3)			83.5 (4)	Projection B&W TV
ZnCdS:Ag	P20	Yellow-Green	350 μs (1)	0.14 (2)	67.0 (2)		Average (7)	20.0 (6)	
Zn_2SiO_4:Mn	P22G	Green	24.5 ms (3)	0.06 (2)	31.8 (2)				Projection Color TV
ZnS:Cu	P31	Green	38 μs (1)	0.22 (2)	50.7 (2)		Very Resistant (7)	20.0 (6)	
Gd_2O_2S:Tb	P43	Pale Green	1 ms (5)	0.18 (6)		No Saturation (8)		>100 (6)	Thomas Elect. PT410
La_2O_2S:Tb	P44	Yellow-Green	1 ms (5)	0.145 (8)		No Saturation (8)			Thomas Elect. PT420

* At 10 Kilovolts and low current density.

1. JEDEC, "Optical Characteristics of Cathode Ray Tube Screens," Publication 16B, August 1971.
2. E. H. Eberhardt, ITT Phosphor Chart & Research Memo 362.
3. "RCA Phosphors," RCA Publication TPM-1508B (1966).
4. A. Pfahnl, "Aging of Electronic Phosphors in Cathode Ray Tubes," Proc. 5th National Conf. on Tube Techniques (1961).
5. P. Seats, "The Cathode Ray Tube - A Review of Current Technology and Future Trends," IEEE Trans. Electron Devices, Sept. 1971.
6. B. Setticase. Thomas Electronics, Inc., Wayne, New Jersey, (Private Correspondence, 17 July 1970).
7. R. A. Bell, "Principles of Cathode Ray Tubes Phosphors and High-Speed Oscillography," Hewlett-Packard Application Note 115.
8. M. Tecotzky, U.S. Radium Co., Hackettstown, New Jersey, (Private Communication, 12 May 1972).

An analysis of the temperature rise of a phosphor screen due to absorption of the kenetic energy of the electron beam has been performed by Elliott[4] but even this analysis fails to quantitatively determine the expected life times of various phosphors due to thermal burn. It merely determines the temperature rise without regard as to whether or not a particular phosphor can withstand that temperature rise. Elliott does make the comment, however, that a temperature rise of 500 degrees C would seem to be a prudent limit.

Electronic aging is an entirely different subject. Electronic aging (sometimes called electronic fatigue or burn) is deterioration of the phosphor's conversion efficiency resulting from crystalline changes due to electron bombardment. Although the exact mechanism of electronic aging is not well understood, it is usually assumed to be the result of either an increased probability of radiationless transitions through the creation of new recombination centers or the deactivation of an activator center by changing its state of ionization. Unlike thermal burn which can be prevented by adequate cooling, electronic aging is unavoidable. The best one can do is to slow the aging process by operating at lower current density levels or at a lower duty cycle.

It has been shown by several authors[5,6] that electronic aging data for phosphors can be represented, to a first approximation, by

$$I = \frac{I_o}{1 + CN}$$

where I_o is the initial unaged intensity of the luminescence, N is the cumulative charge deposited per unit area, and C is a constant of the phosphor called its burn parameter. The burn parameter is a measure of the rate of destruction of the luminance. The reciprocal of the burn parameter is sometimes called the

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[4] W. R. Elliott, "Limitations on High Energy Cathode Ray Tube Beams with Regard to Phosphor Life," Proc. 6th National Symposium, Society for Information Display.

[5] W. Hanle and K. H. Rau, "Light Efficiency and Burn of Phosphors under Electron and Ion Excitation," Z. Phys., Vol. 133 (1952).

[6] K. H. J. Rottgardt, "Destruction of the Luminescence of the Cathode Ray Tube Screens by Electrons," Z. Angew, Phys., Vol. 6 (1954).

phosphor's coulomb rating since it indicates the cumulative charge per unit area necessary to reduce the intensity of the luminescence to one-half of its initial value. The coulomb ratings of a number of high brightness phosphors are also given in Table 47.

If the excitation current density, J, and the duty cycle, D, are known, the half-life of a phosphor screen (in hours) may be readily calculated as

$$T_{\text{half-life}} = \frac{1}{3600\ J\ D}\left(\frac{1}{C}\right)$$

The half-life of a phosphor screen is that cumulative operating time at which the intensity of the luminescence has dropped to one-half of its original value.

It is important to note that electronic aging is unaffected by excitation voltage (at least within the 3 to 50 kilovolt range) or by mode of excitation (either d.c. or raster scanned provided that thermal situations are avoided). Electronic aging is accelerated, however, in an elevated temperature or a poor vacuum environment. Furthermore, a phosphor composition consisting of fine grain particles for high resolution operation is more sensitive to aging than is a coarse grain composition.

Of all the high brightness phosphors listed in Table 47, the two rare earth phosphors, P43 and P44, appear to be the most attractive especially from the viewpoint of long phosphor life at very high brightness levels. Unfortunately, however, published data on these two phosphors are scarce due to their relative newness. Information is generally available only through direct contact with experimental investigators at various research facilities who are presently doing work with these new phosphors. Every indication has been, however, that these two rare earth phosphors, whose spectral emission distributions are shown in figures 87 and 88, are extremely resistant to thermal burn and electronic aging. Furthermore, they do not exhibit the current saturation behavior[3] which is characteristic of silver or copper activated sulphide phosphors such as the P31 and therefore are capable of high brightness operation at lower current levels.

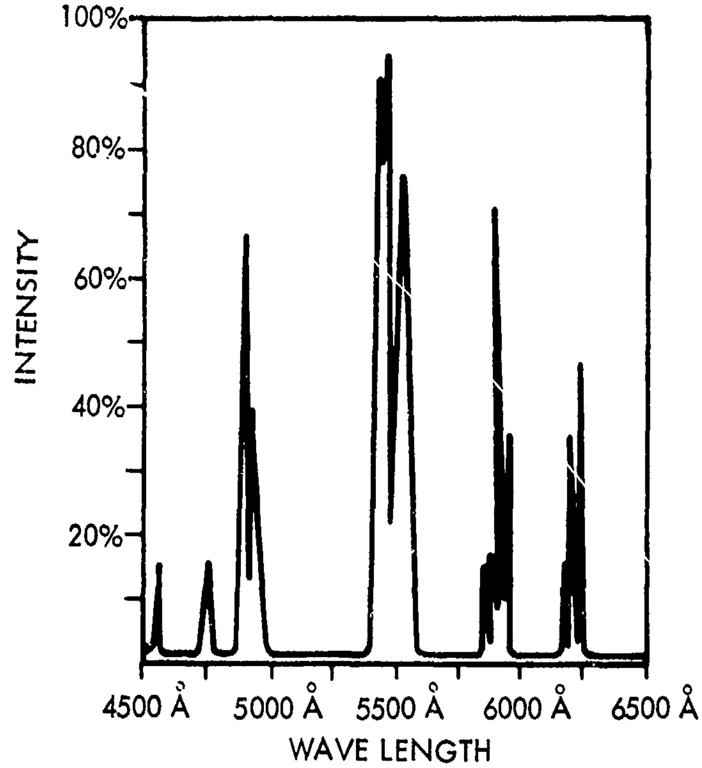
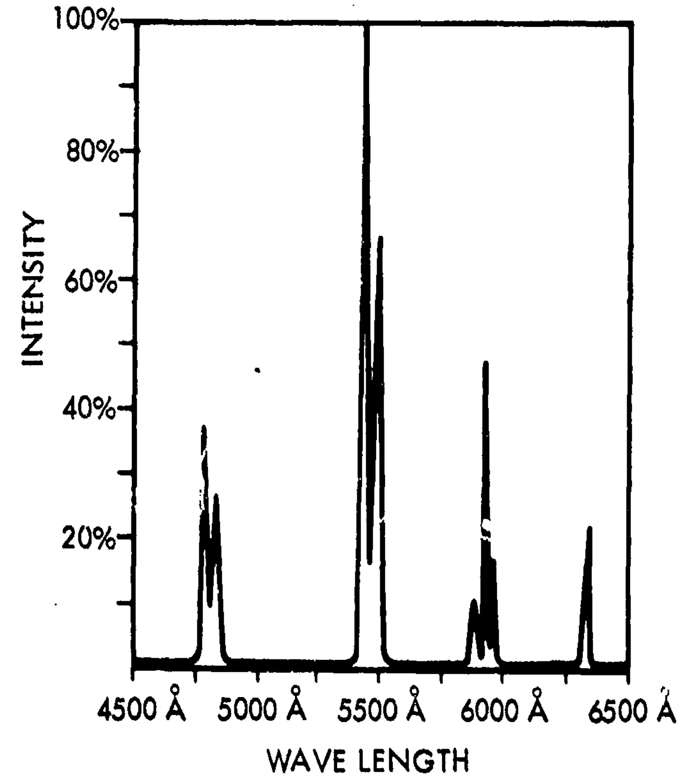


FIGURE 87 P43 SPECTRAL ENERGY DISTRIBUTION



A2-00649

FIGURE 88 P44 SPECTRAL ENERGY DISTRIBUTION

No reference has been found as to the luminous efficiency of either the P43 or the P44 phosphor. Absolute efficiencies have been quoted as shown in Table 47, however, and with these values and the spectral distributions shown in figures 87 and 88, the luminous efficiencies can be estimated by numerical integration. Such a procedure yields 88 lumens/watt excitation for the P43 and 70 lumens/watt excitation for the P44. These values are somewhat higher than those of the other phosphors listed in table 47 further emphasizing the attractiveness of the rare earth compositions. However, since these luminous efficiencies have been analytically derived, it is important to confirm these values by direct experimental evaluation.

An additional feature of the rare earth phosphors is their noncontinuum spectral emission distribution. Line emission such as that shown in figures 87 and 88 suggests the practicality of using a matched narrow band spectral filter as a highly efficient aid for contrast enhancement. Such a filter effectively discriminates against the broadband distribution of natural ambient illumination while passing the more prominent narrowband emission lines of the rare earth phosphors.

A graphical comparison between the high brightness phosphors listed in Table 47 can be readily made by rewriting the equation for the phosphor's half-life in terms of the spot brightness. This yields

$$T_{half\text{-}life}(\text{hours}) = 0.258 \frac{V_{phos}\,\eta_p\,\xi_p}{B_{spot}(\text{ft-L})} \left(\frac{1}{C}\right)$$

where η_p and ξ_p are the absolute conversion efficiency (watts radiated per watt excitation) and the luminous equivalent (lumens radiated per watt radiated) of the phosphor in question and V_{phos} is the phosphor excitation potential. This equation is plotted as a function of spot brightness in Figure 89 for several high brightness phosphors. Note that of the more conventional phosphors the P1 is best in this situation even though its absolute conversion efficiency is low because it exhibits a high coulomb rating. Of course the two rare earth phosphors are even better as indicated if the assumptions in luminous efficiency and coulomb rating are valid. Further investigation into the properties of these two phosphors is necessary to confirm these conclusions.

(Note that because Figure 89 is plotted in terms of spot brightness and not screen (average) brightness, care must be taken to note that a 5150 foot-Lambert spot brightness is necessary to produce a 1100 foot-Lambert screen brightness with the DIGISPLAY.)

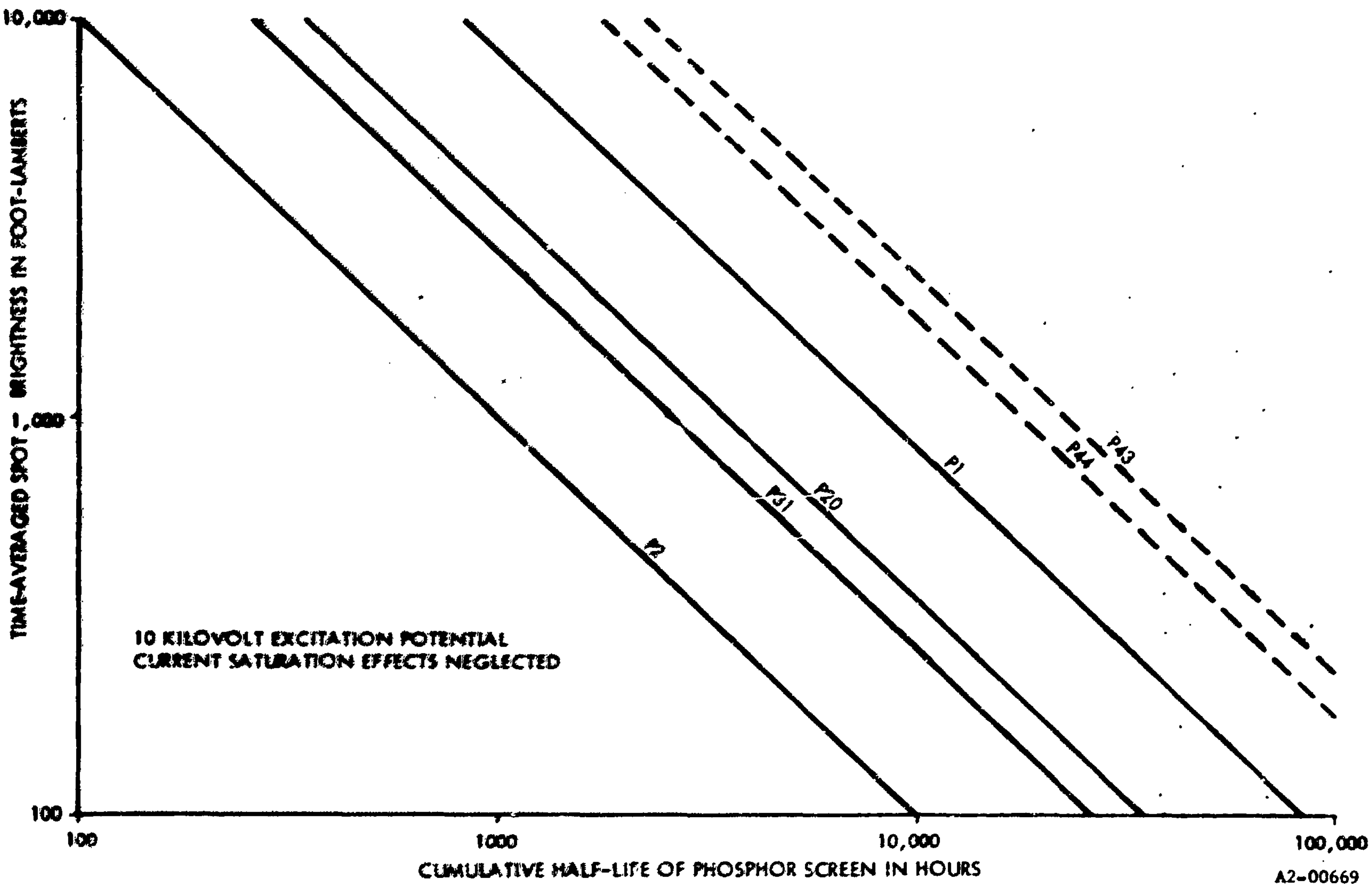


FIGURE 89. HALF-LIFE OF SEVERAL HIGH-BRIGHTNESS PHOSPHOR SCREENS

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